Part IV

Protection

11

Is protection part of the game? Protection against impact using clothing and personal equipment

R M LAING and D J CARR, University of Otago, New Zealand

11.1 Introduction

Prevention of injury during sporting activities attracted greater attention during the late 20th and early 21st centuries than ever before. This resulted from the development of injury analysis and prevention as a discrete area of study, and recognition that injury is preventable; adoption of strategies to reduce costs for treatment, rehabilitation and/or compensation arising from injury (whether sport-related or not), especially in countries where a public-funded, no-fault system of insurance/compensation exists (e.g. New Zealand's Accident Rehabilitation and Compensation Insurance Corporation (ACC)); and exploitation of market opportunities by manufacturers of clothing and personal equipment for sport and tourism (Bentley *et al.*, 2001). As the topic, protective clothing for sport and recreational activity, encompasses products, market share, and applications too diverse to address in one chapter, a decision was made to focus on principles and practices in selected sporting codes where protection against impact was relevant, where the participation rate and/or the number of participants was reportedly high, and where evidence of injury and death resulting from participation in that sport or activity had been published.

Impact is relevant in many sporting and recreational activities, thus the question was, which activities to select – by number of participants perhaps? Estimated world participation numbers for various sporting codes were considered not very useful because of differences in reporting systems (i.e. club membership, training programmes, registered players), and in sources of information (e.g. governing bodies, government agencies, census data). Differences in the participation rates for sporting activities were evident among countries, differences between males and females in and among some countries (e.g. in Canada (Culture Statistics Program, 1998) and Scotland (Sport Scotland, 2001) but not Australia (Australian Sports Commission, 2003)), and differences between adults and young people in and among some countries (e.g. in Canada

(Culture Statistics Program, 1998) and Scotland (Sport Scotland, 2001) but not Australia (Australian Sports Commission, 2003)). In New Zealand, among adults, golf, tennis and touch football were the principal sports, and walking, gardening, exercising (at home or classes), swimming and fishing the principal leisure activities; among young people (aged 5–17 years), soccer, rugby union, cricket and netball were the principal sports, and swimming/surfing, cycling and exercising the principal leisure activities (Sport and Recreation New Zealand, 2004). In Australia, the principal sports were walking, aerobics/fitness, swimming, cycling, tennis, golf (Australian Sports Commission, 2003). In Canada, golf was the principal sporting activity among adults, followed by ice hockey, baseball and swimming; and among children soccer, swimming, ice hockey and baseball were the four most practised sports (Culture Statistics Program, 1998). The principal sports and activities for adults in England early in the 21st century were swimming, keeping fit (aerobics, dance, exercise), cycling, and cue sports (Sport England Research, 2004); whereas in Scotland, walking and swimming were the principal activities, much more common than cycling, football (soccer), golf, dance and other exercise activities (Sport Scotland, 2001). Among Scottish young people, football (soccer), swimming, cycling, running/jogging and basketball/netball/volleyball had the highest reported participation rates (Sport Scotland, 2001).

Cricket, cycling (off-road), equestrian activities, rugby union, snow sports and soccer were selected for further examination. The question ‘Injury prevention in sport: not yet part of the game?’ posed during the early 21st century (Chalmers, 2002), provided the focus around which to review and evaluate protection against impact provided by clothing and other personal protective equipment. Indeed, from the perspective of clothing and/or personal protective equipment prescribed or permitted, injury prevention appears not yet part of most of these sporting codes. This chapter examines the bases for this premise, through an overview of:

- injuries sustained during the selected sporting activities;
- impact protection provided through protective clothing/equipment;
- effects of protective clothing/equipment on human performance;
- guidelines, codes of practice, standards for the selected sporting activities.

Future developments are indicated.

11.2 Analysis of injury sustained during sporting activities

For each of the six sporting codes selected, the incidence and/or rate of injury, body segment/site, and injury mechanism (where stated) from studies published in the scientific literature during the five-year period 2000–2004 are summarized in Table 11.1.

Table 11.1 Injury data for six sporting codes (published 2000–2004)

(a) Cricket
(Stretch, 2003)
Injury rate: 1.9 injuries per player
Body segment: head 4.1%, cervical vertebrae 21%, upper limbs 23.3%, back/trunk 22.8%, lower limbs 49.8%
Mechanism: bowling 41.3%, fielding 28.6%, batting 17.1%

(Orchard *et al.*, 2002)
Injury rate: 19.0–38.5 injuries per 10,000 player hours
Body segment: head/neck batting 13%, fielding 7%; upper limb batting 23%, bowling 9%, fielding 42%; trunk/back batting 2%, bowling 34%, fielding 8%; lower limb batting 59%, bowling 58%, fielding 44%

(Stretch, 2001)
Body segment: back and trunk 24.5%, upper limbs 21.5%, lower limbs 49.7%, head, neck and face 4.3%
Mechanism: bowling 40.5%; batting 21.5%; fielding 25.6%

(Leary and White, 2000)
Injury rate: 57.4 acute injuries per 1000 days played
Body segment: lower limbs 44.9%, upper limbs 29.4%, trunk 20%

(Upadhyay and Tan, 2000)
Mechanism: bat 12, ball 31, fall 12, collision 3, fall on bat handle 1, fall on stumps 1

(b) Cycling (off-road)
(Patel, 2004)
Body segment: lower leg (right)
Mechanism: attempting to remove foot from clip-less pedals after losing control

(Gaulrapp *et al.*, 2001)
Injury rate: 1.1 per 1000 hours of biking
Body segment: Calf/knee 23%, arm 22%, hand 15.2%, hip/thigh 12.8%, head 9.1%, shoulder 8.6%, trunk 6.3%, foot/ankle 3%
Mechanism: slippery terrain 34%, bad judgement 34%, excessive speed 33%, impact with bike 14.3%

(Jeys *et al.*, 2001)
Body segment: shoulder 25%, soft tissue 10%, hand 10%, head 9%

(c) Equestrian
(Johns *et al.*, 2004)
Body segment: head 27, chest 16, vertebra 18, upper limb 36, abdomen 11, pelvic 12, lower limb 34, soft tissue 42, multiple 18
Mechanism: fall 116, kicked/stepped on 16, crushed 7, collision 5

(Petridou *et al.*, 2004)
Body segment: head 47, neck/trunk 68, shoulder/arm 37, hand/fingers 29, thigh/knee/foot/ankle 63
Mechanism: falls 177, other 67

(Ueeck *et al.*, 2004)
Body segment: face 61
Mechanism: kicked 22, fell 28, bucked 3, trampled 6, dragged 2

Table 11.1 (continued)

(Lim *et al.*, 2003)
Body segment: head/spine professional 38%, recreational 56%; trunk professional 13%, recreational 18%; extremities professional 72%, recreational 56%

(Butterwick *et al.*, 2002)
Injury rate: 14.7 per 1000 competitor exposures
Body segment: lower limb 84, upper limb 81, knee 76, spine 55, head/neck 52, shoulder 42, concussion 39, hip 18
Mechanism: bull riding 141, bareback 72, saddle bronco 63, steer wrestling 50, calf roping 8, barrel racing 6, other 111

(Moss *et al.*, 2002)
Injury rate: 5.9 patients per 1000 new attendances
Body segment: upper limb 76, lower limb 58, head/neck 53, multiple 29, thoracolumbar 28, pelvis 13, abdomen 3
Mechanism: fall 205, kicks 29, trod on 14, leading the horse 8, bites 2

(Turner *et al.*, 2002)
Injury rate: flat racing GB 0.17, Ireland 0.15; jump racing GB 1.2, Ireland 0.6 (% per ride)

(Holland *et al.*, 2001)
Body segment: head 124, spine 6, torso 52, limbs 114
Mechanism: fall 153, fall plus other 27, kick 48, bite 2, trampled 6

(Sorli, 2000)
Injury rate: 0.49 per 1000 rider hours (hospital admission rate)
Body segment: head 20%, upper limb 19%, spine 7%, trunk 18%, lower limb 18%, other 17%

(d) Rugby union
(Doyle and George, 2004)
Injury rate: 3.6 per 1000 playing hours (games and training)
Body segment: knee 22%, ankle 18%, lower leg 11%, upper leg 11%, shoulder 11%, neck 7%, foot 4%, pelvis 4%, thumb 4%, wrist 4%, face 4%
Mechanism: tackle 8, ruck 5, running 4, unknown 3, scrum 2, collisions 2

(Jones *et al.*, 2004)
Body segment: head 104, face 79

(Junge *et al.*, 2004)
Injury rate: 2.8 per player per season
Body segment: head 31, spine 40, shoulder 65, upper limb 45, trunk 7, hip/groin 17, lower limb 135

(Muller-Bolla *et al.*, 2003)
Body segment: teeth 206, mandible 83, soft tissue 5

(Bathgate *et al.*, 2002)
Injury rate: 69 per 1000 player hours (matches)
Body segment: head/face 25.1%, knee 14.0%, thigh 13.6%, ankle 10.5%, shoulder 9%
Mechanism: tackle 58.7%, open play 19.6%, ruck/maul 14.7%, scrums/line outs 2.1%

(Babic *et al.*, 2001)
Injury rate: 13.07–33.07 per 1000 player hours (matches)
Body segment: head/neck 23.81%, shoulder 12.70%, upper limb 7.94%, trunk/back 4.76%, knee 14.29%, ankle/foot 20.63%
Mechanism: tackle 47.62%, scrum 9.52%, ruck 15.87%, other 26.99%

(Marshall and Spencer, 2001)
Injury rate: 1.5 per 1000 athlete-exposures

(Sharp *et al.*, 2001)
Injury rate: 87 per 100 scheduled matches

(Bottini *et al.*, 2000)
Injury rate: 2.1% to 2.5% per weekend
Body segment: lower limb 108, ankle 106, head 81, knee 81, face 79
Mechanism: loose play 33%, tackle 25%, maul 19%, ruck 14%, scrum 8%, foul play 2%

(e) Snow sports
(Hagel *et al.*, 2004)
Mechanism: difficult run 549, jumping 723

(Langran and Selvaraj, 2004)
Injury rate: 3.5 per 1000 skier days
Body segment: skier head/torso 12.6%, upper limb 29.3%, lower limb 57.5%; snowboarder head/torso 24.8%, upper limb 57.6%, lower limb 17.6%; ski boarder head/torso 7.5%, upper limb 15.0%, lower limb 77.5%
Mechanism: skier fall 82.9%, lift 2.3%, collision 13.1%, jump 1.1%; snowboarders fall 81.3%, lift 7.2%, collision 9.6%, jump 1.8%; ski boarder fall 87.5%, collision 12.5%

(Siu *et al.*, 2004)
Injury rate: head injury 1.8 per 100,000 skier days, spine injury 5.6 per 100,000 skier days
Body segment: head injuries skiing 15, snowboarding 9, tobogganing 1; spine injuries skiing 36, snowboarding 26, tobogganing 4
Mechanism: head jump 2, fall 10, collision 11, other 2; spine jump 22, fall 32, collision 9, other 3

(Bridges *et al.*, 2003)
Body segment: skiing knee 30%, head 11%, shoulder 9%; snowboarding wrist 23%, head 14%, shoulder/thorax 10%; snowblading knee 26%, leg 20%, shoulder 14%

(DeCou *et al.*, 2003)
Body segment: head injuries 22, upper limb 4, lower limb 5, neck 1, abdomen 1, multiple 18
Mechanism: collision fixed object 13, collision vehicle 11, rollover 3, struck by snowmobile 1, drove off cliff 1

(Hagel *et al.*, 2003)
Injury rate: skiers head 2.23–3.05, brain 1.46–2.78, face 3.41–3.32, neck 1.60–2.15, other 48.05–48.84; snowboarders head 5.60–8.86, brain 4.30–5.62, face 4.16–2.62, neck 1.15–3.87, other 113.49–158.30 (per 100,000 participants)
Body segment: skiers head 234, brain 171, face 441, neck 185, other 5410; snowboarders head 161, brain 114, face 105, neck 69, other 3177

(Cerulli *et al.*, 2002)
Body segment: zygomatic 1, mandibular 1

(Langran and Selvaraj, 2002)
Injury rate: 3.7 injuries per 1000 skier days
Body segment: skiers knee 32.9%, head/face 6.9%, tibia/fibula 5.4%, thumb sprain 5%; snowboarders wrist 14.6%, head/face 12.7%, knee 8.9%, shoulder 4.7%; ski boarders knee 41.9%, tibia/fibula 16.1%, ankle 9.7%, wrist 6.5%

Table 11.1 (continued)

(Macnab *et al.*, 2002)
Body segment: closed head injuries 2, cervical spine injuries 22
Mechanism: falling wearing helmet 48% not wearing helmet 29%; collision wearing helmet 10% not wearing helmet 20%

(Fukuda *et al.*, 2001)
Body segment: snowboarders occipital 304, frontal 119, temporal 57, parietal 6, unknown 148; skiers occipital 139, frontal 126, temporal 63, parietal 13, unknown 101
Mechanism: jumps snowboarder 30% skiers 2.5%; collisions snowboarder 121 skiers 188

(Hentschel *et al.*, 2001)
Injury rate: snowboarders 0.004, skiers 0.005 per 1000 patients (head only)

(f) Soccer
(Pribble *et al.*, 2004)
Body segment: lip 10, mouth 2, gums 1, tooth 1, other 2

(Junge *et al.*, 2004)
Injury rate: 5 match injuries per 1000 match hours
Body segment: head 11, spine 19, shoulder 2, upper limb 13, trunk 7, hip/groin 24, lower limb 185

(Filipe *et al.*, 2003)
Body segment: eye 4
Mechanism: ball 3, foot 1

(Goga and Gongal, 2003)
Body segment: femur 12, tibia 15, soft tissue 104, ankle/foot 12, hip 1

(Cerulli *et al.*, 2002)
Body segment: zygomatic 15, nasal 10, blow-out 4, mandibular 5
Mechanism: elbow-head impact 21, head-head impact 12, head-foot impact 1

(Lilley *et al.*, 2002)
Injury rate: 5.0 (1995) to 12.2 (1994) per 1000 athlete exposure hours
Body segment: ankle 58, shin 44, knee 29, foot 24, spine 18, thigh 17, calf 13, upper limb 12

(Radelet *et al.*, 2002)
Injury rate: 1.7 per 100 athlete exposures (male), 2.3 per 100 athlete exposures (female)
Mechanism: player 27, equipment 29, ground 11

(Elias, 2001)
Injury rate: 184.09 per 1000 player hours (male), 106.25 per 1000 player hours (female)
Body segment: lower limb 65.5%, head/neck 13.6%, upper limb12.3%, trunk 8.6%

(Chomiak *et al.*, 2000)
Body segment: knee 29, ankle 19, spine 9, hand 8, groin 8, thigh 7, shoulder 6, lower leg 5, foot 4, head 2
Mechanism: overuse 18, non-contact 34, contact without foul 15, contact with foul 30

Analysis of injury sustained during sporting activities is problematic. Injuries sustained during participation in various sporting codes derived from prospective, retrospective, or case studies have been reported as the 'incidence' or some form of 'rate', typically not standardised. Both the classification and severity of injury are also typically not standardised. The rate/incidence of injury is reported differently (e.g. as a percentage of patients admitted/treated, as a percentage of the total number of injuries sustained) and may or may not be related to the number of player seasons or player hours or players; the type and location of an injury may or may not be classified using the International Statistical Classification of Diseases and Related Health Problems (ICD) codes (World Health Organization, 1992); the severity of an injury may be classified using one of several systems (e.g. Abbreviated Injury Score (AIS), Maximum Abbreviated Injury Score (MAIS), Injury Severity Score (ISS), New Injury Severity Score (NISS)). (An overview of injury classification is provided by Stevenson *et al.* (2001).) Thus, comparison of data among studies is difficult. Further, neither the protective clothing/equipment worn at the time of the injury event, nor player experience and/or position are included routinely with injury data.

11.3 Impact protection provided through protective clothing and equipment

11.3.1 General principles

The function of impact protective equipment is to absorb the energy of the impact event so that the body segment being protected is either not damaged or, if damaged, the level of damage is 'acceptable'. (An 'acceptable level of damage' varies with the body segment, e.g. contusion may be acceptable at the shin but not the head.) The optimum design of impact protective clothing and equipment requires an understanding of the impact event.

Impact protective clothing and equipment typically combines a rigid outer shell (usually curved) and a foam inner liner (e.g. helmets, shin/leg guards, cricket gloves) or foam padding (e.g. as in boxing). Absorption of impact energy occurs through several mechanisms. Elastic energy is stored in the materials from which the protector is made and returned to the striker when the striker stops moving, resulting in rebound. The curved shape of the rigid shell results in gross deformation and load spreading (i.e. decreases pressure). Deformation of the foam inner (elastic or plastic crushing) increases the contact time between the striker and the protector, reducing peak pressure. Stiffness of the shell is critical. If too stiff, load spreading does not occur. If not sufficiently stiff, permanent damage (and fracture) of the shell can occur. Properties of foam need to be optimised to prevent it 'bottoming out' before the impact energy is absorbed. In a multi-use protector, deformation should be elastic (i.e. not permanent); plastic (permanent) deformation/damage (e.g. fracture) is used as the major energy-absorbing mechanism in single-use protectors.

The use and effectiveness of protective clothing and equipment in reducing the incidence or severity of injury in the selected sports were examined using published scientific literature. This literature reflects distinctly different approaches: (1) application to a product of a national or international standard (or non-standard) laboratory test including adoption of pass/fail criteria in that standard; (2) monitoring and analysis of effects of implementing an injury prevention intervention involving protective clothing and equipment. Results from the first approach are of value when comparing existing products, but of limited use over time because items on the market change relatively quickly and information on brands and models tested typically is not reported thereby precluding identification of a 'best' product. Results from the second approach are much less common, investigations requiring detailed planning (e.g. case-control studies), long time periods, baseline information on patterns of use/non-use, more detailed information from hospitals or other treatment providers such as what was worn at the time of the injury event and whether or not it was in place at impact. Further, changes in behaviour when wearing protective clothing or equipment such as more risk taking, can confound results (e.g. Rees-Jones, 1999; Parkkari *et al.*, 2001). Notwithstanding, only published literature on injury and protective clothing and personal equipment has been reviewed and discussed.

11.3.2 Effectiveness of impact protection in selected sporting codes

Cricket

Few assessments of the effectiveness of personal protective clothing and equipment in preventing cricket-related injury or minimising its severity have been identified. Physiological and other indicators of stress while wearing a protective helmet with a bar and a visor were determined by Davids and Morgan in a laboratory rather than on the field, and because evidence of performance decrements when wearing such a helmet/bar/visor were not apparent, the maximum protection which accrued from these design features was recommended (Davids and Morgan, 1988). An overview on measures to prevent cricket-related injuries published more than 10 years later (Finch *et al.*, 1999) indicated a situation largely unchanged.

Why the dearth of information on protective equipment and its effectiveness when the sport has been in existence for so long, is unclear. Nor is it clear if any reduction in injuries to the hand has resulted from 'improvements' to the gloves of cricketers (e.g. Alexander *et al.*, 1998).

Cycling – off-road

Effects of the mandatory use of helmets by pedal cyclists when cycling on a public road on the incidence and rate of head injury have been well documented, although this is not so for injury to other body sites nor to those cycling off-road (i.e. mountain biking). For pedal cyclists off-road, the incidence of injuries is reportedly higher and the overall severity lower – bruises, lacerations, contusions – than among cyclists on the road (Gaulrapp *et al.*, 2001), although other investigators have reported more fractures of the facial bones which were also more severe among on-road cyclists than among those cycling off-road (e.g. Kronisch *et al.*, 1996; Gassner *et al.*, 1999).

Gloves, special shoes, helmets and body protectors are the protective items available, but the extent of use and link with the incidence and/or severity of injury remain unclear (Pfeiffer and Kronisch, 1995). Nor is it clear whether use of impact-resistant lenses or goggles is common (Kronisch and Pfeiffer, 2002). A helmet is required for competitive events involving mountain biking (Jarvis, 2001) and helmet use is reported to be high in the USA (typically 80–90% according to Kronisch and Pfeiffer (2002)). As the injury events and patterns of injury seem to differ between off- and on-road cycling, both the design and performance of helmets appropriate for each group would likely differ (Kronisch and Pfeiffer, 2002). A conventional cycle helmet does seem to offer some protection to the upper and mid face for on-road cyclists (Thompson *et al.*, 1996), but whether this is true also for those cycling off-road is still to be clarified.

Off-road cycling is a fast-growing recreational activity, one characterised by an ethos among participants of 'protection' (Jarvis, 2001), particularly those in downhill events (e.g. a high proportion of participants in one event in California, USA, wore some form of protection to the face, chest/shoulder, elbow/forearm, knee/shin (30–86%) (Kronisch *et al.*, 1996)). This ethos may contribute to the relatively low reported injury severity.

Equestrian

Protective clothing and personal equipment for use by those engaged in equestrian events includes helmets (with or without a device for face protection), body/torso protectors, shoulder protectors, boots and gloves. A 20-year follow-up study on equestrian-related head injuries in the UK reported a 46% reduction in the number of hospital admissions due to horse-related injuries between 1971/2 and 1991/2 ($p \leq 0.001$) despite an estimated 5% increase in the number of persons riding, attributing this reduction to increased use of, and better, helmets (Chitnavis *et al.*, 1996). The effect of factors other than clothing cannot be excluded from explanations for the change. Nevertheless, the helmet has been the principal focus in most studies on equestrian-related injuries.

In several such studies, the desirability of making mandatory the wearing of a standards-approved helmet has been noted. Mixed results are apparent from studies on the effectiveness of helmets in reducing the incidence and/or severity of injury, depending to some extent on the specificity of study: the severity of head injury, hospital admission or the site of injury. In Australia, Holland *et al.*

(2001) identified no statistically significant difference in the severity of head injury sustained by children admitted to hospital ($n = 232$) between those who wore a helmet at the time of injury and those who did not. Helmet use was associated with a significantly lower hospital admission rate ($n = 221$) in Australia (Lim *et al.*, 2003) with 81% of riders reportedly wearing a helmet at the time of injury, leading Lim *et al.* to conclude the increased use of helmets had contributed to this overall reduction in rate of hospital admission. Similarly, in Virginia, USA, injuries among young people (aged <15 years) from equestrian-related and other activities were examined for a two-year period (November 1990–October, 1992) (Bond *et al.*, 1995). Among those not wearing a helmet, head injuries were more frequent, the severity of injury (modified injury severity scale (MISS score)) was greater, the incidence of hospitalisation was higher and internal injuries greater (Bond *et al.*, 1995). The latter difference was not attributed to helmet use, rather to the possibility of changed behaviour, greater caution by helmet wearers being suggested.

As to site of the injury, maxillofacial injuries seem unlikely to be affected by helmet use. Little effect on maxillofacial injuries was observed in a study in Oregon, USA, where helmet use among the sample of young people was low (81% not wearing a helmet), since little protection is offered to the face by the helmet (Ueeck *et al.*, 2004). And a study of neuro-ophthalmic injuries sustained in equestrian activities in South Australia raised questions about the appropriateness of laws on helmet use and on the adequacy of helmets (and the relevant standards):

> Serious or fatal head injuries do occur despite use of an approved helmet. There is need for further research into the impact forces generated in riding accidents, and into the possibility of improving the performance of helmets.
>
> (Fleming *et al.*, 2001)

The authors suggested further design-related efforts to achieve greater user satisfaction and consequential greater helmet use; and consideration of 'laws' of the code extending use of helmets beyond competition (Fleming *et al.*, 2001).

Low rates of helmet use and high rates of head injury in New Zealand have been reported (Johns *et al.*, 2004) and the authors considered the incidence and severity of head injuries could be reduced by use of appropriate head protection. Head protection during equestrian-related events was not required universally in the USA during the latter part of the 20th century although several standards for helmets for equestrian sports did exist (Hughes *et al.*, 1995), and several equestrian codes did require participants to wear some form of head protection (e.g. United States Pony Club, eventing, professional horse racing/jockeys). The type of helmet to be worn relates to the specific equestrian activity (e.g. helmet with face protection for polo players, given common fractures and facial lacerations) (Costa-Paz *et al.*, 1999).

Development and introduction of body (chest/torso and shoulder) protectors for use in equestrian-related activities occurred during the latter part of the 20th century with only limited evaluation of their effectiveness (Whitlock, 1999). Whitlock noted cross-country riders were injured although all wore some form of body protector; thus the author suggested refinement of these protectors (Whitlock, 1999). Use of protective equipment has been introduced also in professional horse racing, but the effectiveness in reducing injury severity and/or incidence appears mixed: 'at this stage no conclusive data are available on the effectiveness of head or body protectors conforming to the relevant European Standard' (Turner *et al.*, 2002).

Typically, comparisons among the various groups sustaining equestrian-related injuries are not made, the exception being a study in Greece, distinguishing among farming, equestrian and horse-racing groups, each with differences in injury rates, patterns and mechanisms (Petridou *et al.*, 2004). Consequently, different requirements for satisfactory interventions involving protective clothing might easily be overlooked. Further, too little attention seems to have been directed at protecting the hand (gloves) and the feet (boots).

Rugby union

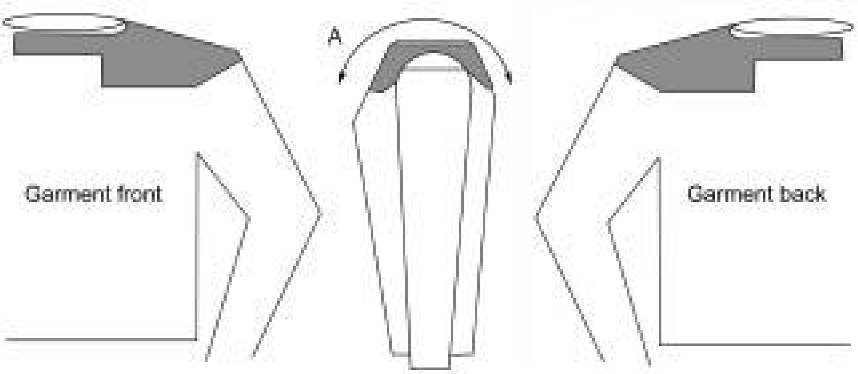
Protective clothing and equipment designed to prevent the incidence and/or reduce the severity of injury sustained among players of rugby union attracted considerable interest in rugby-playing countries such as New Zealand and Australia from the early 1990s, with findings from various investigations incorporated into policies for health promotion (e.g. Simpson *et al.*, 2002), and stimulating international debate (e.g. Quarrie and Chalmers, 2001). Protective equipment worn by rugby players in New Zealand was identified by Marshall *et al.* (2001) and included mouth guards, taping of body joints, shin guards, padded headgear, head tape and support sleeves. This equipment was compared with that worn by US collegiate football players and considered with respect to the rates and types of injury among the two groups (Marshall *et al.*, 2002). The authors acknowledged biases in different exposures, but considered the observed differences to be consistent with the hypothesis that mandatory use of protective equipment reduces the incidence of injury (Marshall *et al.*, 2002).

Specific items of protective clothing and equipment have also been investigated separately: protective headgear, mouth guards and thigh protectors. Studies on the effectiveness of headgear (other than laboratory tests for impact attenuation) are sparse, and a review of headgear published during the late 1990s (Wilson, 1998) provided little evidential link with injury reduction. In Australia, participants in three inter-school competitions for students under 15 years were studied to determine whether wearing protective headgear reduced the incidence of concussion (McIntosh and McCrory, 2001). The headgear at that time was shown not to provide sufficient protection against concussion in rugby at this level (McIntosh and McCrory, 2001). Whether headgear was associated with reduced risk of other forms of head injury such as laceration, abrasion or fracture has also been examined, again in Australia, using a case-control study (164 pairs) and video recording (Jones *et al.*, 2004). Use of headgear was associated with substantial (although not statistically significant) reduction in superficial head and facial injuries, and a higher risk of facial injuries among forwards was reported (Jones *et al.*, 2004).

Investigations of mouth guards can be categorised into one of three groups: laboratory impact attenuation tests (essentially comparisons of different materials and thicknesses, and therefore excluded from further comment in this chapter); extent of use of mouth guards by players; and links with injury. Reasonably high use of mouth guards was reported in a general review of research on these devices published during the late 1990s (Chalmers, 1998), and acceptance of custom-made guards seemed to be favoured (Brionnet *et al.*, 2001). Use of mouth guards among junior rugby players in competition in Australia reportedly increased from 77% to 84% following a 1997–8 use-campaign (Jalleh *et al.*, 2001). Whether use of a mouth guard contributes to injury has also been investigated. For example, McCrory dismissed the link between mouth guard use and prevention of concussion but encouraged ‘a randomised controlled trial of sufficient power to answer this question’, having examined two often-cited papers on the topic (McCrory, 2001). Use of some types of mouth guards has been associated with bone distortion and fractures (e.g. Takeda *et al.*, 2004). And among elite French rugby players, although 65% wore a mouth guard, 30% of players experienced some trauma to the lower or middle part of the face (self-reported) (Muller-Bolla *et al.*, 2003).

Thigh protectors may be worn during Australian Rules Football (ARF) – a game similar to rugby union, and their effectiveness in preventing thigh haematoma was evaluated through a case-control study of two teams of juniors during one season (Mitchell, 2000). The control group suffered nine thigh haematomas whereas the other none, and although the protectors were generally accepted, they were reportedly uncomfortable in hot ambient conditions (Mitchell, 2000).

Those working in rugby union have provided an excellent example of leadership in addressing injury and its reduction in incidence and severity – from modifying ways of playing parts of the game, to training, and use of items of clothing and equipment. The initiative for this has come from Australasia, including the University of Otago in association with the New Zealand Rugby Football Union and the ACC. Working on several fronts, the need for various changes has been carefully documented and provided to the International Rugby Board (IRB) and, as appropriate, changes made to the *Laws of the Game of Rugby Union* (International Rugby Board, 2004). For example, during the 1990s a multidisciplinary team from the University of Otago (academics in biomechanics, clothing and textile sciences, injury prevention, orthopaedics) developed the rationale for introduction/modification of padding permissible for tops, without contributing to an aggressive silhouette (Fig. 11.1).



11.1 Permissible padded area. Source: International Rugby Board, 2004, Reproduced with permission from IRB.

Snow sports

The desirability of using head protection (i.e. a helmet) by those engaged in snow sports generally has been the subject of debate since the mid 1950s, and distinctions in requirements among the various types of snow-related activities have been made (e.g. McCrory, 2002). Those engaged in ski racing, ski jumping, freestyle aerialists and children in all forms of skiing, were identified as likely to benefit most from wearing a helmet (McCrory, 2002). Benefits for adult recreational skiers were considered not to have been demonstrated by some research groups (e.g. Rees-Jones, 1999; McCrory, 2002; Xiang and Stallones, 2003) although others do not share this view (e.g. Siu *et al.*, 2004) (the latter resulted from a review of injury rather than a review of helmet use and related injury). Helmet use among a group of injured Canadian skiers, snowboarders and snowbladers did not differ significantly, nor was there any evidence of an increase in the incidence of neck injuries with helmet use (a claim sometimes made) among this group (Bridges *et al.*, 2003). These results held when adjusted for age and activity (Bridges *et al.*, 2003).

The effect of helmet use on injury in specific snow sports has been the subject of two studies: injury severity in skiers and snowboarders (Hagel *et al.*, 2004), and the incidence of head/face and cervical spine injuries in young skiers and snowboarders (Macnab *et al.*, 2002). The first was a case-control study (Quebec, Canada) in which the focus was on injury severity and circumstance other than injuries to the head and neck. Matching was on the ski area, activity, day, age and sex; no evidence that wearing a helmet increased the risk of severe injury or high-energy crash circumstances was identified (Hagel *et al.*, 2004). The second study sought to identify whether adverse effects of wearing a helmet (e.g. reduced peripheral vision, reduced acuity in hearing) led to an increase in the incidence and/or severity of cervical spine injury, a decrease in head injury, and/or an increase in collisions among young skiers and snowboarders (i.e. <13 years old) (Macnab *et al.*, 2002). In spite of the small number of cases ($n = 70$), the authors reported a decreased risk of head injury associated with wearing head protection and no increase in the risk of cervical spine injury (Macnab *et al.*, 2002). One issue in this study was whether use of a helmet by child skiers (additional mass) contributed to spinal injury; no evidence supporting the claim was identified.

Most focus has been on injury to the head and face with much less on injury to other body sites. Clearly, opportunities exist for investigation of these other sites.

Soccer

During the 1980s, using a randomised case-controlled study, Ekstrand and colleagues assessed the effectiveness of seven approaches to preventing injury among soccer players, two of which were related to clothing/personal protective equipment (leg guards, training shoes, ankle taping for those with previous ankle injury or ankle instability (Ekstrand and Gillquist, 1984)). The relative contributions of the different components to reduced injury were, unfortunately, not determined (Ekstrand and Gillquist, 1984). However, some years later, Boden (1998) reported that 90% of fractures sustained by soccer players occurred while the players were wearing shin guards, that no player reported the shin guard was out of place at the time, and that in about half the cases, impact was adjacent to the guard, often lateral to it. This finding suggested the guards provide inadequate coverage, a point further confirmed by Cattermole *et al.* (1996), noting that 85% of players in their survey of 100 adult football players with tibial fractures had been wearing shin guards.

Headgear as a preventive intervention for those playing soccer was the subject of several investigations during the early 21st century, typically laboratory trials of products available commercially or under development (e.g. Broglio *et al.*, 2003; Naunheim *et al.*, 2003), although some writers consider use of headgear is not possible because of the need to ‘play the ball’ (e.g. Cerulli *et al.*, 2002). Shin pads have also been subject to laboratory tests to establish impact attenuation. A discussion of results from these studies has not been included.

11.4 Effects of protective clothing and equipment on human performance

While offering various levels of protection against known hazards, the use of protective clothing influences several aspects of human performance both at a general level (thermoregulatory responses, vision and other cognitive functions, manual dexterity, gross motor behaviour), and at performance levels *specific* to the sporting activity. General responses to wearing protective clothing result from the greater mass of clothing and protective products, the greater thermal resistance of the clothing and protective products, the shift from the skin surface to the garment surface of sweat to be vaporised (with a consequential lesser cooling effect), incremental differences in dimensions of garments and those of the body with increasing layers of clothing and consequential reduced body flexibility. The literature on these effects is extensive, principally emanating from various occupational groups, including the military. The literature on effects of clothing on performance levels specific to any sporting activity is far from complete, and the review of clothing, textiles and human performance by Laing and Sleivert (2002) provides a useful overview of developments in understanding of the topic for the period 1980–2000. What is clear from the review is the need to consider simultaneous, but not necessarily predictable, effects on the body of clothing systems.

Recognition of the need for simultaneous integration of components of an assembly began to be included in various standards on protective clothing from the early 21st century (e.g. British Standards Institution, 2002; International Organization for Standardization, 2004). These examples relate to workplace protective clothing rather than sport *per se* (although a sporting arena is the workplace for a professional sportsperson). Recognition of ergonomic principles, satisfactory garment fit (including specification of sizing requirements), minimising garment mass, for example, is typical of workplace standards and codes of practice (e.g. British Standards Institution, 2003). With a few exceptions (e.g. International Rugby Board, 2004), this is typically not so with standards, codes of practice and guidelines for sport.

For further information on thermal aspects of clothing/textiles see Chapter 9.

11.5 Guidelines, codes of practice, standards

Guidelines, codes of practice, standards and standard test methods vary principally in the level of compliance required – voluntary, required for participation in a sporting activity at the national or international level, or required by statute in a particular country. They also vary in subject and in scope.

11.5.1 Guidelines

A guideline is simply a direction, a lead to be followed. Compliance with guidelines is typically voluntary. However, if the guidelines are based on requirements from a related source, compliance would be unquestioned. The *Manufacturer Trademark Guidelines Manual* (International Olympic Committee, 2003) is one such example, The International Olympic Committee (IOC) routinely developing guidelines for use by manufacturers of clothing and personal equipment for the Olympic Games. Specifications in various Olympic Charter rules and bye-laws are interpreted in the Guidelines, along with practical, direct instruction to manufacturers and suppliers (e.g. dimensions of trademarks, letters or words; the

11.2 Manufacturer trademarks on competition clothing permitted by IOC. Source: International Olympic Committee, 2003. Reproduced with permission from IOC.

number of times the symbols/words/brands may appear on any one object; permitted locations for symbols/words/brands) (Fig. 11.2).

11.5.2 Codes of practice, national and international requirements

Each sport has a code of practice in which the rules for conduct of that sport are stated. These include rules for the sport itself (i.e. how the sporting event is conducted), and in most cases, reference to clothing and personal protective equipment to be worn or permitted. The international associations (e.g. the International Rugby Board, Netball International, Fédération Equestre Internationale, International Cricket Council, International Ski Federation) provide codes of practice for international events, and these codes typically form the basis of national codes. The extent to which clothing and personal protective equipment is specified is highly variable among the different codes; from minimal in the case of cricket (Marylebone Cricket Club, 2003) (i.e. protective items permitted but not required), yachting (i.e. focused on the mass of clothing and equipment and how mass is determined (International Sailing Federation, 2001)); to highly prescribed visually in the case of international equestrian events (Fédération Equestre Internationale, 2000, 2003a,b, 2004), prescribed in garment construction methods and fabrics used in the case of international ski competitions (International Ski Federation, 2004); and with highly prescribed product test methods in the case of rugby union (International Rugby Board, 2004). The following example is for suits for ski jumping:

> **4 Ski-jumping suits**
> All portions of the ski jumping suit must be made of the same material ... must close by means of a zipper at the front ... The width of the zipper may not exceed 10 mm ... The thickness of all parts of the suit must be the same. No additional chemical ... or mechanical treatment of the material or suits is allowed ... Seams may only exist in order to join portions of the suit ... The thickness of the suit may not exceed 5.0 mm.
>
> **4.1 Air permeability of the suit material**
> The material of a jumping suit must show a minimum air permeability ... which is the same from the outside in and from the inside out. Minimum air permeability is established as follows:
> The unstretched fabric ... 40 liters per m^2/sec under 10 mm of water pressure. This value is compulsory at the time of distribution by the manufacturer that means at the time of plumbing. At controls in competitions it must not be less than 35 liters ...
>
> **4.2 Material, fabric**
> **... Outer layer/first layer**
> The outer fabric for the ski jumper is a bi-elastic warp-knit fabric, called Charmeuse ... 81% Polyamid [sic] gloss dtex 44f12, 19% Elasthane [sic] (Lycra) dtex 44f1, weight 180/190 g/m^2 approx.
>
> (International Ski Federation, 2004)

Departure from a set of international laws by the relevant association in any one country is evident from time to time (e.g. in the case of rugby union, the mandatory wearing of a mouth guard by all players (New Zealand Rugby Football Union, 2004)).

> **Law 4 - Player's clothing**
> **1 Additional items of clothing**
> (f) A player may wear a mouth guard or dental protector
> The wearing of mouth guards is compulsory for all players at all levels of New Zealand Domestic Rugby.
>
> (New Zealand Rugby Football Union, 2004)

The International Football Association lists items of clothing; shin guards to 'provide a reasonable degree of protection'; colours which distinguish the position of goalkeeper, and makes non-permissible slogans or advertising on undershirts which are revealed when removing the jersey, and sleeveless jerseys (International Football Association Board, 2004).

Thus, with few exceptions, the laws of various games contain reference to clothing/protective clothing revolving around protection, appearance, definition of position, and advertising.

11.5.3 Standards and standard test methods

A standard is defined in the ISO/IEC Guide 2:1996 as 'a document, established by consensus and approved by a recognized body, that provides, for common and repeated use, rules, guidelines or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context' (World Standards Service Network, 2004). Standards are varied in character, subject and medium. They

> cover several disciplines: dealing with all technical, economic and social aspects of human activity ... are developed by technical committees ... result from participation: ... consensus [among] ... producers, users, laboratories, public authorities, consumers ...; are reviewed periodically or as dictated by circumstance to ensure their currency ... ;
> ... have a reference status: in commercial contracts and *in court in the event of a dispute*;
> ... have national or international recognition: standards are documents which are recognized as valid – nationally, regionally or internationally, as appropriate ...;
> are not mandatory, but are for voluntary application ... *implementation may be obligatory (such as in fields connected with safety).*
> (World Standards Service Network, 2004, emphasis added)

The relevance of standards to clothing and textiles in sport is three-fold. They may (1) specify characteristics and properties of a product(s) used in sport (e.g. British Standards Institution, 2000a,b); (2) specify a test method to be used in determining the properties of a product (e.g. to determine properties of protectors for horse riders (British Standards Institution, 2000b)), or (3) be guidelines in the form of a standard (e.g. Standards New Zealand, 2004).

Unusually, a standard test method may be included in the 'law' of some sports. For example, Schedule 1 of Regulation 12 of the *Laws of the Game of Rugby Union* (International Rugby Board, 2004) is quite specific as to permissible clothing and its performance properties. The latter are included as the 'standard performance specification for specific items of player's clothing', acknowledging the intrinsic hazard of the sport, recognising ergonomic issues, and prescribing methods for testing various products (International Rugby Board, 2004). Apart from the test methods, much is ill-defined. Textile matters are imprecise – 'stretch type material', 'non-rigid fabric', 'soft and thin materials' – and the duration of conditioning under controlled ambient temperature and humidity is inconsistent with widely accepted standard requirements (British Standards Institution, 1992) (i.e. 4–24 hours at 20 ± 2 °C, 60 ± 5% R.H. compared with 24 hours at 20 ± 2 °C, 65 ± 2% R.H., respectively).

Many standards are narrow in scope, addressing one performance property (e.g. resistance of shin guards to impact (British Standards Institution, 2001a)), or one test method (e.g. test for impact protectors (British Standards Institution, 1998)). The definition of scope in some standards does indicate the existence of hazards which may occur concurrently, and during the early 21st century, standards organisations began to include approaches to product selection when faced with multiple concurrent hazards. In the case of hand protection, for example:

> End users should select gloves based on a risk assessment involving the identification of hazards and determination of risk of exposure to those hazards. End users can then determine the relevant performance properties and acceptable levels of performance for those properties.
>
> NOTE: No glove can have optimum properties in all respects; the performance requirements can be contradictory. End users are expected to ignore recommendations for performance properties that are not important to them and make compromises as needed among other performance properties.
>
> (International Organization for Standardization, 2004)

Guidelines for the selection of hand protection (Appendix B of the draft standard) included conducting a hazard and risk assessment of the setting/workplace (International Organization for Standardization, 2004). Adverse physiological effects of wearing protective clothing continue to be examined (e.g. Holland *et al.*, 2002; Havenith *et al.*, 2003), and provide further scientific evidence for informing standards development organisations.

Standard methods determining protection against impact relevant to the six sporting codes which are the focus of this chapter are listed in Table 11.2. In the impact testing sections of these standards, the impact energy (or velocity or drop-height), the shape and size of the striker and anvil, and a pass/fail criterion are usually given. The impact event itself may be determined and described in a number of ways:

- the protector (e.g. shin pad, glove) is mounted on an anvil, impacted by a striker (guided free-fall), and the maximum force transmitted through the protector measured;
- the helmet or other item of headgear is mounted on a guided, free-falling head-form that impacts an anvil, and the acceleration of the helmet is measured; or
- the helmet is mounted on a fixed head-form, impacted by a falling striker (guided free-fall), and either the acceleration of the striker or the force transmitted through the helmet measured.

11.5.4 Status of standards, codes of practice, guidelines

The status of any standard or other code in any country depends on three factors: whether it has been referred to in a statute for that jurisdiction, whether a standard is cited in the code of practice for that sport, and whether legislation protecting consumers in general might apply. First, standards on sport products are most pertinent to legislation on health and safety in the workplace (the sports venue considered as the workplace of a professional sportsperson). For example, in New Zealand, land-based employees involved in sporting activities are covered by the Health and Safety in Employment Act (New Zealand Government, 1992), and the New Zealand Health and Safety in Employment Regulations (New Zealand Government, 1995). These regulations require

Table 11.2 Standard test methods for determining protection against impact

Standard	Aim
(a) Cricket	
AS/NZS 4499.1:1997 Protective headgear for cricket: Helmets (Standards Australia/Standards New Zealand, 1997a)	Mitigate the effects of a blow to the head by a cricket ball
AS/NZS 4499.2:1997 Protective headgear for cricket: Temple protectors (Standards Australia/Standards New Zealand, 1997b)	Mitigate the effects of a blow to the side of the head by a cricket ball
AS/NZS 4499.3:1997 Protective headgear for cricket: Faceguards (Standards Australia/Standards New Zealand, 1997c)	Mitigate the effects of a blow to the face by a cricket ball
BS 6183-3:2000 Protective equipment for cricketers: Leg protectors for batsmen, wicket-keepers and fielders, and thigh, arm and chest protectors for batsmen (British Standards Institution, 2000a)	Reduce severity of injuries from accidental impact by cricket balls
BS 6183-4:2001 Protective equipment for cricketers: Gloves for batsmen (British Standards Institution, 2001a)	Reduce severity of injuries from accidental impact by cricket balls
(b) Cycling	
AS/NZ 2063:1996/Amd 1:1996 Pedal cycle helmets (Standards Australia/Standards New Zealand, 1996)	Minimise the severity of head injuries from hazards associated with pedal cycling
ASTM F1952-00 Standard Specification for helmets used for down hill mountain bike racing	Provide higher protection levels to the head and face compared to a helmet for road cyclists
BS EN 1078:1997 Helmets for pedal cyclists and for users of skateboards and roller skates (British Standards Institution, 1997a)	Absorb the energy of an impact, thus reducing the risk of injury to the head
(c) Equestrian	
AS/NZS 3838:1998 Helmets for horse riding and horse-related activities (Standards Australia/Standards New Zealand, 1998)	Mitigate the effects of an impact to the head
BS EN 1384:1997 Specification for helmets for equestrian activities(British Standards Institution, 1997b)	Specifies requirements for protective helmets, that may or may not have a peak, for people involved in equestrian activities

Table 11.2 (continued)

Standard	Aim
BS EN 13158:2000 Protective clothing: Protective jackets, body and shoulder protectors for horse riders Requirements and test methods. (British Standards Institution, 2000b)	Designed to reduce injury from blunt impacts, falls and kicks
(d) Rugby Union	
Standard performance specification for specific items of players' clothing. Regulation 12: Provisions relating to players' dress (International Rugby Board, 2004)	Reduce the severity and frequency of injuries from impacts with other players or the playing surface
(e) Snow-sports	
BS EN 1077:1996 Specification for helmets for alpine skiers (British Standards Institution, 1996)	Reduce the risk of injury to the skull and part of the head surrounded by the helmet
(f) Soccer	
BS EN 13061:2001 Protective clothing: Shin guards for association football players Requirements and test methods (British Standards Institution, 2001b)	Significantly reduce the severity of laceration, contusion and puncture caused by impacts

designers, manufacturers and distributors to take all steps practicable to ensure that the products provide the protection claimed. Legislation on workplace health and safety in several other countries is similar in scope (e.g. Australian Federal Government, 1991; British Government, 1974; Council of the European Communities, 1989; United States Congress, 2004). However, in the UK, the individual professional sports reportedly self-regulate, and employers or those organising sporting events are required to provide a 'safe' environment, the key phrases being 'so far as is reasonably practicable' and 'duty of care'. Such a view is also reflected in *The Rules of Hockey* (International Hockey Federation, 2003), under 'Responsibility and Liability':

> Emphasis is placed on safety. Everyone involved in the game must act with consideration for the safety of others. Relevant national legislation must be observed. Players must ensure that their equipment does not constitute a danger to themselves or to others by virtue of its quality, materials or design. The International Hockey Federation (FIH) does not accept responsibility for any defects or non-compliance … Any verification … before a match is limited to ensuring an overall appearance of compliance and sporting requirements.
>
> (International Hockey Federation, 2003)

Whether or not a standard is cited in the code of practice for that sport is relevant (e.g. specified for players of rugby union (International Rugby Board, 2004)) as is the extent to which legislation protecting consumers in general might apply (e.g. legislation on product safety, consumer guarantees). In marking products for use in rugby union, the IRB standard approval must be designated, and where the garment is sold in the European Union, the CE mark must be shown and 'it is the responsibility of the manufacture [sic] to comply with the PPE directive' (International Rugby Board, 2004).

Useful Standards websites are:

International Organization for Standardization: http://www.iso.ch
British Standards Institution: http://www.bsi-global.com
American National Standards Institute: http://www.ansi.org
American Society for Testing and Materials: http://www.astm.org
Standards Australia: http://www.standards.com.au
Standards New Zealand: http://www.standards.co.nz

11.6 Discussion and further developments

Developments in two general areas seem likely: prevention of injury and minimising the severity of injury through protective clothing and equipment, and commercial developments with the constraining influences of compliance.

Prevention of injury and minimising the severity of injury through the development and use of protective clothing and equipment requires greater collaboration among those in health fields dealing with the injured, standards developers and organisations, designers and manufacturers of protective clothing and equipment, and the sporting bodies themselves. While much of the data on injury resulting from participation in the six sporting codes selected is informative, its usefulness is limited by the lack of accompanying information on what was worn at the time of the injury and whether the item covered the body site at that time. Developers of standards require detailed information on hazards of the physical environment where the sporting activity occurs which can be used to modify and refine laboratory test methods so that these better reflect impact events. Any rationale for two or more different standards reportedly reflecting requirements of the same sporting codes needs to be made explicit.

Perhaps of greatest concern is that, among the six codes which form the basis of this chapter and based on documentation available to the public, the IRB seems the sole international sporting organisation to have used findings from the scientific literature in enhancing recommendations and requirements for clothing and personal protective equipment. In most codes, the focus is on appearance and managing advertising. Perhaps systematic investigations of sports-related injury, including evaluations of effectiveness of interventions, depend on the existence of a national organisation with an imperative for reducing injury incidence/severity (e.g. ACC in New Zealand) and thus a willingness to provide financial support for such studies. The collaboration evident among scientists, the New Zealand Rugby Football Union, the ACC and the players themselves provides an excellent model.

Commercialisation of the various sporting activities is expected to increase, driven by an increasing market size and increasing competition for market share. Compliance with a range of national and/or international requirements is likely to become more apparent, although monitoring compliance will be challenging. Citation of or reference to international or de facto international standards in international sporting codes is expected. Perhaps textile and other protective products for specialised applications which are part of this commercial activity will be developed using the rich sources of information in the scientific literature.

11.7 Acknowledgements

Mr Jack Mace for assistance with document collection and sorting.

11.8 References

Alexander, S., Underwood, D. and Cooke, A. J. 1998. Cricket glove design. In *The engineering of sport: Design and development*, edited by Haake, S. J. Oxford, UK: Blackwell Science Ltd: 15–22.

American Society for Testing and Materials 2000. ASTM F1952-00 Standard specification for helmets used for down hill mountain bicycle racing. *ASTM International*.

Australian Federal Government 1991. Occupational Health and Safety (Commonwealth Employment) Act 1991. Canberra: Australian Federal Government.

Australian Sports Commission 2003. Participation in exercise recreation and sport – annual report 2003. http://www.ausport.gov.au (23 September 2004).

Babic, Z., Misigoj-Durakovic, M., Matasic, H. and Jancic, J. 2001. Croatian rugby project. Part II: injuries. *Journal of Sports Medicine and Physical Fitness*, 41(3): 392–398.

Bathgate, A., Best, J. P., Craig, G. and Jamieson, M. 2002. A prospective study of injuries to elite Australian rugby union players. *British Journal of Sports Medicine*, 36(4): 265–269.

Bentley, T., Page, S., Meyer, D., Chalmers, D. J. and Laird, I. 2001. How safe is adventure tourism in New Zealand? An exploratory analysis. *Applied Ergonomics*, 32(4): 327–338.

Boden, B. P. 1998. Leg injuries and shin guards. *Clinics in Sports Medicine*, 17(4): 769–777.

Bond, C. R., Christoph, R. A. and Rodgers, B. M. 1995. Pediatric equestrian injuries: assessing the impact of helmet use. *Pediatrics*, 95(4): 487–489.

Bottini, E., Poggi, E. J., Luzuriaga, F. and Secin, F. P. 2000. Incidence and nature of the most common rugby injuries sustained in Argentina (1991–1997). *British Journal of Sports Medicine*, 34(2): 94–97.

Bridges, E. J., Rouah, F. and Johnston, K. M. 2003. Snowblading injuries in eastern Canada. *British Journal of Sports Medicine*, 37(6): 511–515.

Brionnet, J-M., Roger-Leroi, V., Tubert-Jeannin, S. and Garson, A. 2001. Rugby players' satisfaction with custom-fitted mouthguards made with different materials. *Community Dentistry and Oral Epidemiology*, 29(3): 234–238.

British Government 1974. Health and Safety at Work Act 1974. London: HMSO.

British Standards Institution 1992. BS EN 20139:1992; ISO 139:1973 *Textiles – Standard atmospheres for conditioning and testing*. London: British Standards Institution.

British Standards Institution 1996. BS EN 1077:1996 *Specification for helmets for alpine skiers*. London: British Standards Institution.

British Standards Institution 1997a. BS EN 1078:1997 *Helmets for pedal cyclists and for users of skateboards and roller skates*. London: British Standards Institution.

British Standards Institution 1997b. BS EN 1384:1997 *Specification for helmets for equestrian activities*. London: British Standards Institution.

British Standards Institution 1998. BS EN 1621-1:1998 *Motorcyclists' protective clothing against mechanical impact. Part 1: requirements and test methods for impact protectors*. London: British Standards Institution.

British Standards Institution 2000a. BS 6183-3:2000 *Protective equipment for cricketers. Part 3: leg protectors for batsmen, wicketkeepers and fielders, and thigh, arm and chest protectors for batsmen*. London: British Standards Institution.

British Standards Institution 2000b. BS EN 13158:2000 *Protective clothing: Protective jackets, body and shoulder protectors for horse riders – requirements and test methods*. London: British Standards Institution.

British Standards Institution 2001a. BS 6183-4:2001 *Protective equipment for cricketers. Part 4: gloves for batsmen*. London: British Standards Institution.

British Standards Institution 2001b. BS EN 13061:2001 *Protective clothing: shin guards for association football players – requirements and test methods*. London: British Standards Institution.

British Standards Institution 2002. BS 7971-1:2002 *Protective clothing and equipment for use in violent situations and in training. Part 1: general requirements*. London: British Standards Institution.

British Standards Institution 2003. BS EN 420:2003 *Protective gloves – general requirements and test methods*. London: British Standards Institution.

Broglio, S. P., Ju, Y-Y., Broglio, M. D. and Sell, T. C. 2003. The efficacy of soccer headgear. *Journal of Athletic Training*, 38(3): 220–224.

Butterwick, D. J., Hagel, B., Nelson, D. S., LeFave, M. R. and Meeuwisse, W. H. 2002. Epidemiologic analysis of injury in five years of Canadian professional rodeo. *American Journal of Sports Medicine*, 30(2): 193–198.

Cattermole, H. R., Hardy, J. R. W. and Gregg, P. J. 1996. The footballer's fracture. *British Journal of Sports Medicine*, 30(2): 171–175.

Cerulli, G., Carboni, A., Mercurio, A., Perugini, M. and Becelli, R. 2002. Soccer-related craniomaxillofacial injuries. *Journal of Craniofacial Surgery*, 13(5): 627–630.

Chalmers, D. J. 1998. Mouthguards – protection for the mouth in rugby union. *Sports Medicine*, 25(5): 339–349.

Chalmers, D. J. 2002. Injury prevention in sport: not yet part of the game? *Injury Prevention*, 8(Suppl. IV): iv22–iv25.

Chitnavis, J. P., Gibbons, C. L. M. H., Hirigoyen, M., Parry, J. L. and Simpson,

A. H. R. W. 1996. Accidents with horses: what has changed in 20 years? *Injury Prevention*, 27(2): 103–105.

Chomiak, J., Junge, A., Peterson, L. and Dvorak, J. 2000. Severe injuries in football players. *American Journal of Sports Medicine*, 28(5): S58–S68.

Costa-Paz, M., Aponte-Tinao, L. and Muscolo, D. L. 1999. Injuries to polo riders: a prospective evaluation. *British Journal of Sports Medicine*, 33(5): 329–332.

Council of the European Communities 1989. Council Directive 89/656/EEC of 30 November 1989 on the minimum health and safety requirements for the use of workers of personal protective equipment at the workplace. http://www.europa.eu.int (24 September 2004).

Culture Statistics Program, 1998. Sport participation in Canada. http://www.pch.gc.ca (22 September 2004).

Davids, D. and Morgan, M. 1988. The effects of helmet design and bowling speed on indices of stress in cricket batting. *Ergonomics*, 31(11): 1665–1671.

DeCou, J. M., Fagerman, L. E., Ropele, D., Uitvlugt, N. D., Schlatter, M. G. and Connors, R. H. 2003. Snowmobile injuries and fatalities in children. *Journal of Pediatric Surgery*, 38(5): 784–787.

Doyle, C. and George, K. 2004. Injuries associated with elite participation in women's rugby over a competitive season: an initial investigation. *Physical Therapy in Sport*, 5(1): 44–50.

Ekstrand, J. and Gillquist, J. 1984. Prevention of sports injuries in football players. *International Journal of Sports Medicine*, 5(Suppl.): 140–144.

Elias, A. R. 2001. Ten-year trend in USA Cup soccer injuries: 1988–1997. *Medicine and Science in Sports and Exercise*, 33(3): 359–367.

Fédération Equestre Internationale 2000. *General regulations*. http://www.fei.ch (22 September 2004).

Fédération Equestre Internationale 2003a. *Rules for dressage events*. http://www.fei.ch (22 September 2004).

Fédération Equestre Internationale 2003b. *Rules for eventing*. http://www.fei.ch (22 September 2004).

Fédération Equestre Internationale 2004. *Rules for jumping events*. http://www.fei.ch (22 September 2004).

Filipe, J. A. C., Rocha-Sousa, A., Falcão-Reis, F. and Castro-Correia, J. 2003. Modern sports eye injuries. *British Journal of Ophthalmology*, 87(11): 1336–1339.

Finch, C. F., Elliott, B. C. and McGrath, A. C. 1999. Measures to prevent cricket injuries. *Sports Medicine*, 28(4): 263–272.

Fleming, P. R., Crompton, J. L. and Simpson, D. A. 2001. Neuro-ophthalmological sequelae of horse-related accidents. *Clinical and Experimental Ophthalmology*, 29(4): 208–212.

Fukuda, O., Takaba, M., Saito, T. and Endo, S. 2001. Head injuries in snowboarders compared with head injuries in skiers: a prospective analysis of 1076 patients from 1994 to 1999 in Niigata, Japan. *American Journal of Sports Medicine*, 29(4): 437–440.

Gassner, R. J., Hackl, W., Tuli, T., Fink, C. and Waldhart, E. 1999. Differential profile of facial injuries among mountainbikers compared with bicyclists. *Journal of Trauma Injury, Infection, and Critical Care*, 47(1): 50–54.

Gaulrapp, H., Weber, A. and Rosemeyer, B. 2001. Injuries in mountain biking. *Knee Surgery, Sports Traumatology, Arthroscopy*, 9(1): 48–53.

Goga, I. E. and Gongal, P. 2003. Severe soccer injuries in amateurs. *British Journal of Sports Medicine*, 37(6): 498–501.

Hagel, B., Pless, B. and Platt, R. W. 2003. Trends in emergency department reported head and neck injuries among skiers and snowboarders. *Canadian Journal of Public Health*, 94(6): 458–462.

Hagel, B., Pless, I. B., Goulet, C., Platt, R. and Robitaille, Y. 2004. The effect of helmet use on injury severity and crash circumstances in skiers and snowboarders. *Accident Analysis and Prevention*, 37(1): 103–108.

Havenith, G., Ueda, H., Sari, H. and Inoue, Y. 2003. Required clothing ventilation for different body regions in relation to local sweat rates. In *Challenges for protective clothing*, edited by EMPA. Montreux, Switzerland: European Society of Protective Clothing (CD).

Hentschel, S., Hader, W. and Boyd, M. 2001. Head injuries in skiers and snowboarders in British Columbia. *Canadian Journal of Neurological Sciences*, 28(1): 42–46.

Holland, A. J. A., Roy, G. T., Goh, V., Ross, F. I., Keneally, J. P. and Cass, D. T. 2001. Horse-related injuries in children. *Medical Journal of Australia*, 175(11): 609–612.

Holland, E. J., Laing, R. M., Lemmon, T. L. and Niven, B. E. 2002. Helmet design to facilitate thermoneutrality during forest harvesting. *Ergonomics*, 45(10): 699–716.

Hughes, K. M., Falcone, R. E., Price, J. and Witkoff, M. 1995. Equestrian-related trauma. *American Journal of Emergency Medicine*, 13(4): 485–487.

International Football Association Board 2004. *Laws of the game*. http://www.fifa.com (21 September 2004).

International Hockey Federation 2003. *Rules of hockey including explanations – effective from 1 January 2004*. http://www.fihockey.org (21 September 2004).

International Olympic Committee 2003. *International Olympic Committee Manufacturer Trademark Guidelines Manual*. Lausanne, Switzerland: International Olympic Committee.

International Organization for Standardization 2004. ISO/DIS 22613 *Protective clothing – general test methods and performance requirements*. Geneva, Switzerland: International Organization for Standardization.

International Rugby Board 2004. *The laws of the game of rugby union*. http://www.irb.com (21 September 2004).

International Sailing Federation 2001. *The racing rules of sailing for 2001–2004*. http://www.sailing.org (23 September 2004).

International Ski Federation 2004. *Specifications for competition equipment and commercial markings 2004–2005*. http://www.fis-ski.com (23 September 2004).

Jalleh, G., Donovan, R. J., Clarkson, J., March, K., Foster, M. and Giles-Corti, B. 2001. Increasing mouthguards usage among junior rugby and basketball players. *Australian and New Zealand Journal of Public Health*, 25(3): 250–252.

Jarvis, C. 2001. Commentary. Mountain biking injuries in rural England. *British Journal of Sports Medicine*, 35(3): 199.

Jeys, L. M., Cribb, G., Toms, A. D. and Hay, S. M. 2001. Mountain biking injuries in rural England. *British Journal of Sports Medicine*, 35(3): 197–199.

Johns, E., Farrant, G. and Civil, I. 2004. Animal-related injury in urban New Zealand. *Injury, International Journal of the Care of the Injured*, 35(12): 1234–1238.

Jones, S. J., Lyons, R. A., Evans, R., Newcombe, R. G., Nash, P., McCabe, M. and Palmer, S. R. 2004. Effectiveness of rugby headgear in preventing soft tissue injuries to the head: a case-control study and video cohort study. *British Journal of Sports*

Medicine, 38(2): 159–162.

Junge, A., Cheung, K., Edwards, T. and Dvorak, J. 2004. Injuries in youth amateur soccer and rugby players – comparison of incidence and characteristics. *British Journal of Sports Medicine*, 38(2): 168–172.

Kronisch, R. L. and Pfeiffer, R. P. 2002. Mountain biking injuries – an update. *Sports Medicine*, 32(8): 523–537.

Kronisch, R. L., Chow, T. K., Simon, L. M. and Wong, P. F. 1996. Acute injuries in off-road bicycle racing. *American Journal of Sports Medicine*, 24(1): 88–93.

Laing, R. M. and Sleivert, G. G. 2002. Clothing, textiles and human performance. *Textile Progress*, 32(2): 1–132.

Langran, M. and Selvaraj, S. 2002. Snow sports injuries in Scotland: a case-control study. *British Journal of Sports Medicine*, 36(2): 135–140.

Langran, M. and Selvaraj, S. 2004. Increased injury risk among first-day skiers, snowboarders, and skiboarders. *American Journal of Sports Medicine*, 32(1): 96–103.

Leary, T. and White, J. A. 2000. Acute injury incidence in professional county club cricket players (1985–1995). *British Journal of Sports Medicine*, 34(2): 145–147.

Lilley, K., Gass, E. and Locke, S. 2002. A retrospective injury analysis of state representative female soccer players. *Physical Therapy in Sport*, 3(1): 2–9.

Lim, J., Puttaswamy, V., Gizzi, M., Christie, L., Croker, W. and Crowe, P. 2003. Pattern of equestrian injuries presenting to a Sydney teaching hospital. *Australia and New Zealand Journal of Surgery*, 73(8): 567–571.

Macnab, A. J., Smith, T., Gagnon, F. A. and Macnab, M. 2002. Effect of helmet wear on the incidence of head/face and cervical spine injuries in young skiers and snowboarders. *Injury Prevention*, 8(4): 324–327.

Marshall, S. W. and Spencer, R. J. 2001. Concussion in rugby: the hidden epidemic. *Journal of Athletic Training*, 36(3): 334–338.

Marshall, S. W., Waller, A. E., Loomis, D. P., Feehan, M., Chalmers, D. J., Bird, Y. N. and Quarrie, K. L. 2001. Use of protective equipment in a cohort of rugby players. *Medicine and Science in Sports and Exercise*, 33(12): 2131–2138.

Marshall, S. W., Waller, A. E., Dick, R. W., Pugh, C. B., Loomis, D. P. and Chalmers, D. J. 2002. An ecologic study of protective equipment and injury in two contact sports. *International Journal of Epidemiology*, 31(3): 587–592.

Marylebone Cricket Club, 2003. *The laws of cricket* (2000 Code, 2nd edition). http://www.lords.org (21 September 2004).

McCrory, P. 2001. Do mouthguards prevent concussion? *British Journal of Sports Medicine*, 35(2): 81–82.

McCrory, P. 2002. The role of helmets in skiing and snowboarding. *British Journal of Sports Medicine*, 36(5): 314.

McIntosh, A. S. and McCrory, P. 2001. Effectiveness of headgear in a pilot study of under 15 rugby football union. *British Journal of Sports Medicine*, 35(3): 167–169.

Mitchell, B. 2000. Efficacy of thigh protectors in preventing thigh haematomas. *Journal of Science and Medicine in Sport*, 3(1): 30–34.

Moss, P. S., Wan, A. and Whitlock, M. R. 2002. A changing pattern of injuries to horse riders. *Emergency Medical Journal*, 19: 412–414.

Muller-Bolla, M., Lupi-Pegurier, L., Pedeutour, P. and Bolla, M. 2003. Orofacial trauma and rugby in France: epidemiological survey. *Dental Traumatology*, 19(4): 183–192.

Naunheim, R. S., Ryden, A., Standeven, J., Genin, G., Lewis, L., Thompson, P. and Bayly, P. 2003. Does soccer headgear attenuate the impact when heading a soccer ball? *Academic Emergency Medicine*, 10(1): 85–90.

New Zealand Government 1992. *Health and Safety in Employment*. Wellington: New Zealand Government.

New Zealand Government 1995. The Health and Safety in Employment Regulations 1995. Wellington: New Zealand Government.

New Zealand Rugby Football Union 2004. *Domestic safety law variations*. http://www.nzrugbynet.co.nz (21 September 2004).

Orchard, J., James, T., Alcott, E., Carter, S. and Farhart, P. 2002. Injuries in Australian cricket at first class level 1995/1996 to 2000/2001. *British Journal of Sports Medicine*, 36(4): 270–275.

Parkkari, J., Kujala, U. M. and Kannus, P. 2001. Is it possible to prevent sports injuries? Review of controlled clinical trials and recommendations for future work. *Sports Medicine*, 31(14): 985–995.

Patel, N. D. 2004. Mountain bike injuries and clipless pedals: a review of three cases. *British Journal of Sports Medicine*, 38(3): 340–341.

Petridou, E., Kedikoglou, S., Belechri, M., Ntouvelis, E., Dessypris, N. and Trichopoulos, D. 2004. The mosaic of equestrian-related injuries in Greece. *Journal of Trauma Injury, Infection, and Critical Care*, 56(3): 643–647.

Pfeiffer, R. P. and Kronisch, R. L. 1995. Off-road cycling injuries – an overview. *Sports Medicine*, 19(5): 311–325.

Pribble, J. M., Maio, R. F. and Freed, G. L. 2004. Parental perceptions regarding mandatory mouthguard use in competitive soccer. *Injury Prevention*, 10: 159–162.

Quarrie, K. L. and Chalmers, D. J. 2001. Letter. Impact of professionalism on injuries in rugby union. *British Journal of Sports Medicine*, 35(6): 450.

Radelet, M. A., Lephart, S. M., Rubinstein, E. N. and Myers, J. B. 2002. Survey of the injury rate for children in community sports. *Pediatrics*, 110(3): 1–11.

Rees-Jones, A. 1999. Skiing helmets. *British Journal of Sports Medicine*, 33(1): 3.

Sharp, J. C. M., Murray, G. D. and Macleod, D. 2001. A unique insight into the incidence of rugby injuries using referee replacement reports. *British Journal of Sports Medicine*, 35(2): 34–37.

Simpson, J., Chalmers, D. J. and Waller, A. E. 2002. The New Zealand rugby injury and performance project: developing 'tackling rugby injury', a national injury prevention program. *Health Promotion Journal of Australia*, 13(1): 44–50.

Siu, T. L. T., Chandran, K. N., Newcombe, R. L., Fuller, J. W. and Pik, J. H. T. 2004. Snow sports related head and spinal injuries: an eight-year survey from the neurotrauma centre for the Snowy Mountains, Australia. *Journal of Clinical Neuroscience*, 11(3): 236–242.

Sorli, J. M. 2000. Equestrian injuries: a five year review of hospital admissions in British Columbia, Canada. *Injury Prevention*, 6: 59–61.

Sport England Research 2004. *Participation in sport – results from the general household survey 2002*. http://www.sportengland.org (22 September 2004).

Sport and Recreation New Zealand 2004. *Combined sport and physical activity surveys – 1998, 2000*. http://www.sparc.org.nz (22 September 2004).

Sport Scotland, 2001. *Sports participation in Scotland*. http://www.sportscotland.org.uk (23 September 2004).

Standards Australia/Standards New Zealand 1996. AS/NZS 2063:1996/Amd 1:1996 *Pedal cycle helmets*. Wellington: Standards New Zealand.

Standards Australia/Standards New Zealand 1997a. AS/NZS 4499.1:1997 *Protective* *headgear for cricket. Part 1: Helmets*. Wellington: Standards New Zealand.

Standards Australia/Standards New Zealand 1997b. AS/NZS 4499.2:1997 *Protective headgear for cricket. Part 2: Temple protectors*. Wellington: Standards New Zealand.

Standards Australia/Standards New Zealand 1997c. AS/NZS 4499.3:1997 *Protective headgear for cricket. Part 3: Faceguards*. Wellington: Standards New Zealand.

Standards Australia/Standards New Zealand 1998. AS/NZS 3838:1998 *Helmets for horse riding and horse-related activities*. Wellington: Standards New Zealand.

Standards New Zealand 2004. SNZ HB 8669:2004 *Risk management for sport and recreation*. Wellington: Standards New Zealand.

Stevenson, M., Segui-Gomez, M., Lescohier, I., Di Scala, C. and McDonald-Smith, G. 2001. An overview of the injury severity score and the new injury severity score. *Injury Prevention*, 7(1): 10–13.

Stretch, R. A. 2001. Incidence and nature of epidemiological injuries to elite South African cricket players. *South African Medical Journal*, 91(4): 336–339.

Stretch, R. A. 2003. Cricket injuries: a longitudinal study of the nature of injuries to South African cricketers. *British Journal of Sports Medicine*, 37(3): 250–253.

Takeda, T., Ishigami, K., Ogawa, T., Nakajima, K., Shibusawa, M., Shimada, A. and Regner, C. W. 2004. Are all mouthguards the same and safe to use? The influence of occlusal supporting mouthguards in decreasing bone distortion and fractures. *Dental Traumatology*, 20(3): 150–156.

Thompson, D. C., Nunn, M. E., Thompson, R. S. and Rivara, F. P. 1996. Effectiveness of bicycle safety helmets in preventing serious facial injury. *Journal of the American Medical Association (JAMA)*, 276(24): 1974–1975.

Turner, M., McCrory, P. and Halley, W. 2002. Injuries in professional horse racing in Great Britain and the Republic of Ireland during 1992–2000. *British Journal of Sports Medicine*, 36(6): 403–409.

Ueeck, B. A., Dierks, E. J., Homer, L. D. and Potter, B. 2004. Patterns of maxillofacial injuries related to interaction with horses. *Journal of Oral and Maxillofacial Surgery*, 62: 693–696.

United States Congress 2004. The Occupational Safety and Health Act of 1970. Washington, DC: United States Federal Government.

Upadhyay, V. and Tan, A. 2000. Cricketing injuries in children: from the trivial to the severe. *New Zealand Medical Journal*, 113(1105): 81–83.

Whitlock, M. R. 1999. Injuries to riders in the cross country phase of eventing: the importance of protective equipment. *British Journal of Sports Medicine*, 33(3): 212–216.

Wilson, B. D. 1998. Protective headgear in rugby union. *Sports Medicine*, 25(5): 333–337.

World Health Organization 1992. *International statistical classification of diseases and related health problems* (10th rev. edn). Geneva, Switzerland: World Health Organization.

World Standards Service Network 2004. General information. http://www.wssn.net (22 September 2004).

Xiang, H. and Stallones, L. 2003. Deaths associated with snow skiing in Colorado 1980–1981 to 2000–2001 ski seasons. *International Journal of Care of the Injured*, 34(12): 892–896.

12

Protection against cold

I HOLMÉR, Lund Technical University, Sweden

12.1 Introduction

Cold is a hazard to human health. Cold environments may adversely affect physiological functions, work performance and wellbeing. The major threat is cooling, be it local skin cooling, extremity cooling or whole body cooling. Likewise the strategy for cold protection is prevention of cooling and maintenance of heat balance at acceptable temperature levels. In combination with certain sports, in particular of endurance type, cold protection becomes a delicate balancing with the demands for high heat dissipation to the environment in order to prevent excessive body heating. Clothing must meet the special requirements for protection in various sports, for example ice hockey and downhill skiing. Clothing must also be designed and function in a way that minimally restricts the body movements necessary for the particular sports.

This chapter deals with protection against cold in sporting events. The cold environment and its climatic components are defined and described. The heat exchange between the human body and the environment is presented and the various forms of heat losses and methods for their determination are defined. Levels of heat production are presented for various types of winter sports. A method for calculation of required clothing insulation is described. Thermal properties of clothing determine the various forms for heat losses. The essential factors are defined and methods for their determination are presented. The effects of fibres, fabrics, construction and clothing design are discussed. In a final section, the ultimate strategy for staying well protected against cold, yet enabling sufficient surplus body heat to be dissipated, is presented.

12.2 The cold environment

A cold environment can be defined as an environment in which larger than normal heat losses can be expected. The climatic factors governing heat losses are:

- air temperature
- mean radiant temperature
- air velocity
- humidity.

Factors such as snow and rainfall affect heat exchange primarily by interaction with clothing heat transfer properties.

Heat exchange between the body and the environment takes place at the skin surface by convection, radiation, conduction, evaporation and via the airways (respiration).

12.2.1 Convection

Air in contact with a warm surface warms up and becomes less dense. The warm air rises and causes a chimney effect close to the skin surface (natural convection). Wind strongly interferes with this process and increases convection. The following principal equation applies to convective heat exchange (C):

$$C = h_c \cdot (t_{sk} - t_a) \tag{12.1}$$

where h_c is the convective heat transfer coefficient in W/m^2 ºC, t_{sk} is the mean skin temperature in ºC and t_a is the air temperature in ºC. The value of h_c depends primarily on wind for nude surfaces. In calm air, a normal value for h_c is 3–4 W/m^2 ºC. With clothed surfaces, heat transfer becomes more complex. This is discussed in a following section.

12.2.2 Radiation

Heat is transported as electromagnetic waves from a warm to a cold surface. This radiative heat exchange (R) is determined by the following equation:

$$R = h_r \cdot (t_{sk} - \bar{t}_r) \tag{12.2}$$

where h_r is the radiative heat transfer coefficient in W/m^2 ºC and $\bar{t}_r$ is the mean radiant temperature in ºC. The value of h_r is relatively constant at about 4 W/m^2 ºC and independent of, for example, wind. Clothing affects radiative heat transfer and will be discussed later.

12.2.3 Conduction

Heat is transmitted between two surfaces in contact with each other if there is a temperature difference. For a standing or moving person, the body surface area in contact with another surface is negligible (foot soles). For a seated or reclining person, larger areas contact other surfaces and determination of conductive heat exchange may be justified.

12.2.4 Evaporation

By producing sweat that evaporates on the skin surface the human body can get rid of significant amounts of heat. Sweating is a necessary and powerful mechanism for body cooling in response to high levels of body heat production and/or external heat loads. The formula for evaporative heat exchange (*E*) in air is defined by the following formula:

$$E = h_e \cdot (p_{sk} - p_a) = 16.6 \cdot h_c \cdot (p_{sk} - p_a) \tag{12.3}$$

where h_e is the evaporative heat transfer coefficient, p_{sk} is the water vapour pressure at the skin surface in kPa, and p_a is the ambient water vapour pressure in kPa. For normal air a constant relation exists between convection and evaporation and can be expressed by $16.6 \cdot h_c$ (Lewis relation).

In a cold environment the large temperature gradient between the skin surface and the environment is usually sufficient to allow control of heat balance by convection and radiation. Additional sweat evaporation may be required only at extremely high levels of metabolic heat production. For efficient cooling the evaporated sweat needs to be transported as water vapour through the clothing and air layers adjacent to the skin and/or by convection through openings in the clothing. The effects of clothing on evaporative heat transfer will be discussed later.

12.2.5 Airway heat exchange

Breathing air at low temperatures cools the airways of the respiratory system and adds to the skin heat losses. The cold air is warmed and saturated with water vapour in the lungs and airways. The amount of airway cooling increases with lowered air temperature. It increases with increased minute ventilation, but remains a relatively constant fraction of the metabolic heat production. The airway heat losses may amount to 15–20% of the total heat production of the body. Airway heat losses are not under any physiological control, but may be reduced by simple covers of mouth and nose or by special masks for heat and moisture regain. Airway cooling is a risk factor in cross-country skiing and the main criteria for setting temperature limits. The International Ski Federation has decided that the lowest temperature for competition events shall be −18 °C.

A classification of the cold stress can be based on the auxiliary heat losses imposed by the gradually colder environment. Compared with conditions at +20 °C, heat loss approximately doubles at +5 °C, increases three times at −10 °C and four times at −25 °C, everything else kept constant. Conditions at +20 °C represent indoor conditions with the body in good thermal balance. At the lower temperatures the body cannot preserve heat balance, tissues lose heat and temperatures drop.

12.3 Energy metabolism, heat production and physical work

Assessment of the protection requirements in a cold environment requires information about the energy metabolism of the individual. Metabolic rate is related to the intensity of physical work and can be easily determined from measurements of oxygen consumption. Tables are readily available that allow its estimation during different types of activity (ISO 8996, 2004). With few exceptions, the values for metabolic rate also indicate the level of metabolic heat production. In most types of muscular work the mechanical efficiency is negligible. Typically, winter sports may involve activities from very low to extremely high levels of heat production. For certain types of sports, for example downhill skiing, the event is of such short duration (less than 1–2 minutes) that prevention of local cooling becomes more important than the overall heat balance.

Table 12.1 can be used for a rough estimation of the metabolic rate and associated heat production in various types of sports and forms of physical activity.

Table 12.1 Examples of metabolic energy production associated with different types of sports and physical activities. Classes modified according to ISO 8996 (2004). Values refer to a standard person with 1.8 m^2 body surface area

Class	Average metabolic rate (W/m^2)	Examples
0 Resting	65	Sleeping, resting
1 Low	100	Spectators at sporting events, casual walking (speed up to 3.5 km/h), shooting, curling, fishing
2 Moderate	165	Hiking (average person), walking at a speed of 3.5 km/h to 5.5 km/h, alpine skiing (average person)
3 High	230	Intermittent activities in ball games (bandy, ice hockey), walking at a speed of 5.5 km/h to 7 km/h, hiking (well-trained)
4 Very high	290	Climbing, running or walking at a speed greater than 7 km/h, alpine skiing (well-trained)
Very, very high (2 h)	400	Long-distance events in cross-country skiing
Intensive work (15 min)	475	Sprint events in cross-country skiing
Exhaustive work (5 min)	600	Sprint events in skating

12.4 The human heat balance equation

Appropriate protection against cold is provided when the human body is in heat balance at acceptable levels of body temperatures (for example, skin and core temperatures). This implies that heat losses are equal to metabolic heat production. The following equation describes the heat balance:

$$S = M - C - R - E - RES \tag{12.4}$$

where S is the rate of change in body heat content, M is the metabolic heat production, C is the convective heat exchange, R is the radiative heat exchange and RES is the airway heat loss, all in W/m^2. For simplicity, external mechanical work rate and conductive heat exchanges are neglected.

Equations for determination of C, R, E and RES have been described, but the role of clothing is yet to be defined. There are two principal thermal properties that determine clothing effects on heat exchanges by convection, radiation and evaporation: thermal insulation and evaporative resistance.

Thermal insulation (I) defines the resistance to heat transfer by convection and radiation by clothing layers. It accounts for the resistance to heat exchange in all directions and over the whole body surface. It is an average of covered as well as uncovered body parts. This unique definition allows the introduction of clothing in the heat balance equation. The insulation of clothing and adjacent air layers is defined as the total insulation value (I_T) and is defined by the following equation:

$$I_T = \frac{t_{sk} - t_a}{R + C} \tag{12.5}$$

The value of I is given in m^2 ºC/W or in clo-units (1 clo = 0.155 m^2 ºC/W). This definition and the clo unit was introduced more than 60 years ago in order to facilitate the understanding of the human balance (Gagge *et al.*, 1941; Newburgh, 1949).

Evaporative resistance (R_e) defines the resistance to heat transfer by evaporation and vapour transfer through clothing layers. As for insulation, it also refers to the whole body surface. In reality, the property is a resistance to vapour transfer. Heat transfer takes place only when sweat evaporates at the skin and is transported to the environment by diffusion or convection. The evaporative resistance of clothing layers and adjacent air layers (R_{eT}) is defined by the following equation. The unit is Pa m^2/W.

$$R_{eT} = \frac{p_{sk} - p_a}{E} \tag{12.6}$$

An alternative way of expressing clothing resistance to water vapour transfer is by using the moisture permeability index, i_m. The index provides a relation between evaporative and dry heat resistance of clothing systems. The following relation applies:

$$R_{eT} = \frac{I_T}{i_m \cdot L} = \frac{0.06}{i_m} \cdot \left(\frac{I_a}{f_{cl}} + I_{cl} \right) \qquad (12.7)$$

where L is Lewis number (16.7 ºC/kPa).

The value of i_m varies between 0 for impermeable ensembles and 1 for a wet surface in strong wind. The value of i_m reduces with thickness of still air layers and number of fabric layers. Accordingly, cold protective clothing with several layers offers high resistance to evaporative heat transfer.

The human heat balance can now be written as follows. It can readily be seen how clothing affects heat exchange and the effect can be quantified.

$$S = M - \frac{t_{sk} - t_a}{I_T} - \frac{p_{sk} - p_a}{R_{eT}} - RES \qquad (12.8)$$

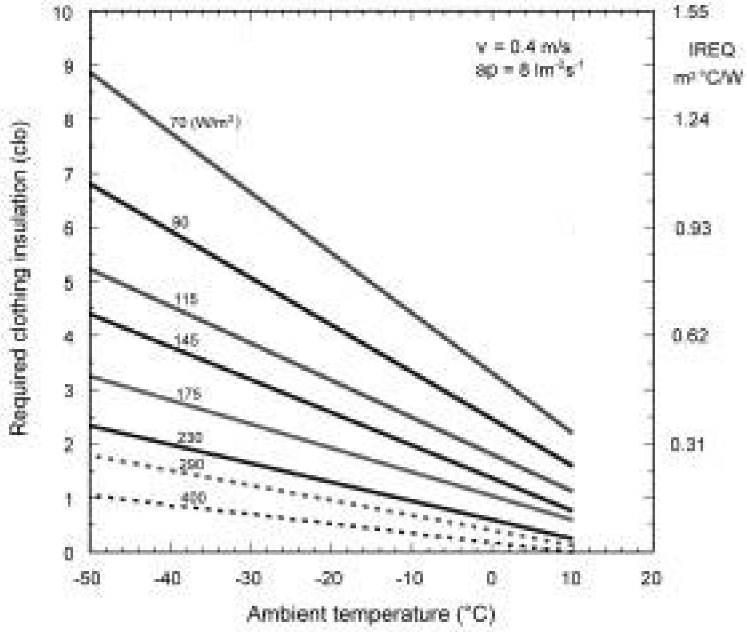
Heat balance is achieved when the value of S is zero. This can occur for various combinations of the variables of the equation. However, only certain values for the physiological variables (M, t_{sk} and p_{sk}) are compatible with acceptable and tolerable conditions. These conditions can be analysed in terms of various scenarios for activity, climate and clothing.

12.5 Requirements for protection

Based on the human heat balance equation, the required values for I_T and R_{eT}, for combinations of activity and climate can be calculated. As previously mentioned, the appropriate strategy for efficient cold protection is to optimise clothing insulation, so as to avoid or minimise evaporative heat exchange. The value of p_{sk} in the equation becomes only slightly higher than ambient p_a and the evaporative heat loss will be small. Accordingly, the possible values of ambient t_a for which heat balance can be maintained is primarily determined by the clothing insulation value.

A method (and international standard) has been proposed that determines the required clothing insulation (IREQ) as a function of ambient climate and activity (ISO/DIS 11079, 2004). Heat balance of the body is assumed for normal values for body and skin temperatures. Furthermore, heat losses take place primarily by convection and radiation, whilst sweating is minimal. Figure 12.1 presents the required clothing insulation (IREQ values) for combinations of activity and air temperature. This way of determining the insulation requirement implies that clothing must provide this final insulation level when used during the prevailing conditions. Also, the IREQ value specifies the requirement for the clothing layers only. The boundary air layer at the clothing surface is calculated separately. The justification for this is explained in the section about clothing measurements.

Insulation requirements increase steeply at low activity levels in the cold. The low levels of metabolic heat production require high thermal resistances to create heat balance. In contrast, high activity levels produce much heat that



12.1 Required clothing insulation at various work intensities at low temperatures in still air (modified from ISO/DIS 11079). At very high activity levels (broken lines) the real insulation must be higher in order to prevent unacceptable local skin cooling.

must be transferred instantly to the environment, in order to prevent overheating of the body. This is best done by reducing the insulative layer. There is a minimal level of insulation (clothing), however, that must be provided even at very high activity levels. This is to prevent direct skin cooling and discomfort from low skin temperatures. With such minimal insulation, increased sweating and sweat evaporation must complement the other heat losses for preserving good heat balance and avoiding overheating. The broken lines at the bottom of Fig. 12.1 indicate that this insulation level may be too low to protect against *local* cooling.

Wind accelerates heat loss from a warm surface. In many sports the travelling speed may create a significant relative air velocity around the body surface. Accordingly, surface layers of the body should provide high resistance to air penetration in order to minimise microclimate cooling. The outer garment of the clothing ensemble, preferably, should be made of materials with low air permeability.

Similarly, wet fabrics and layers reduce insulation and increase heat losses. In particular, the surface layer of the outer garment should be water repellent or waterproof.

12.6 Measurements of clothing performance

The practical question now is how can actual clothing be tested in order to evaluate to what extent it meets the requirements for cold protective clothing. This will be answered in the following section.

12.6.1 Thermal insulation

Traditionally thermal properties of textiles are measured with a heated hot plate (ISO 5085-1, 1989; ISO 11092, 1993). Such information is of limited value for prediction of clothing properties. Heat flow through a clothing system is three-dimensional and passes through combinations of layers of fabrics and air that vary in thickness. Form, fit, design and coverage of the body are other factors modifying the insulation value. As previously mentioned, the specific definition of clothing insulation requires the resistance to heat fluxes over the whole body surface area to be measured. For this purpose a thermal manikin is required (Fig. 12.2).

12.2 Walking thermal manikin for measurement of thermal insulation of clothing.

The use of thermal manikins in clothing research has a long history (Holmér, 2004). Today more than 100 thermal manikins are in use worldwide. Two international standards describe measurement of thermal insulation of clothing with a thermal manikin: ISO 9920 (1993) and ISO 15831 (2003). In principle, a full-scale model of the human body is densely covered with resistance wires. Typically, the body surface is divided in anatomical body parts that form independent zones. The surface temperature of each zone is measured and a regulation program supplies the electrical power required for maintaining a constant skin temperature (usually about 34 ºC). The manikin is placed in a climatic chamber under defined conditions. From measurements of manikin skin temperature, ambient air temperature and power consumption during steady state conditions, the insulation of the clothing on the manikin can be determined (equation 12.5).

The following insulation values apply:

- *Total thermal insulation of clothing* (I_T) defines insulation of all layers surrounding the body including adjacent air layers.
- *Basic thermal insulation of clothing* (I_{cl}) defines the insulation of the skin to clothing surface layers only.
- *Air layer insulation* (I_a) defines the insulation of the boundary air layer on the nude body surface.

The following relation applies:

$$I_T = I_{cl} + \frac{I_a}{f_{cl}} \tag{12.9}$$

where f_{cl} is the clothing area factor. Total body surface area expands when clothing layers are put on the body. Typically f_{cl} varies from 1.0 to 1.5 for heavy and thick winter clothing.

Normally, I_a is measured with the nude thermal manikin and I_T measured with the test clothing. The I_{cl} value for the test clothing is calculated from equation 12.9. The f_{cl} value is best determined with a photogrametric method or with body scanning.

12.6.2 Evaporative resistance

Evaporative resistance of fabrics is measured with a heated water hotplate (ISO 5085-1, 1989; ISO 11092, 1993). Sweating manikins are available, but results show the relative effect of sweating on heat exchange rather than the actual evaporative resistance (Meinander, 2000; McCullough, 2001). A wetted cover on a dry, thermal manikin may provide reliable values for the permeability index (Breckenridge and Goldman, 1977). A combination of fabric and manikin measurements may allow the determination of clothing evaporative resistance (Umbach, 1992).

12.6.3 Wind resistance

The air permeability of fabrics can be measured using ISO-EN 9237. The effects of form, fit, stiffness, layers and other factors are not accounted for.

12.6.4 Water resistance

Water resistance of fabrics is measured using ISO 20811. A new test is proposed that measures water resistance of full ensembles (ENV 14360, 2002).

12.6.5 Standards for protective clothing against cold and foul weather

A large number of international standards have been developed for various types of clothing properties. A few of them deal with protection against cold and foul weather.

ENV 342. Protective clothing – Ensembles and garments for protection against cold. 2003.
ENV 343. Protective clothing – Protection against foul weather. 1998.
ENV 14058. Protective clothing – Garments for protection against cool environments. 2002.
EN 511. Protective gloves against cold. 2004.

ENV 342 requires measurement of thermal insulation, air permeability and evaporative resistance. The two latter properties are measured on fabrics. Thermal insulation is measured with a manikin either static or walking. Equations for wind correction are provided. Clothing performance is indicated by marking the label with the insulation value and the class of air permeability. Evaporative resistance is optional.

ENV 343 requires measurement of water permeability and evaporative resistance of the fabric. Performance is indicated by marking with classes for the measured values.

ENV 14058 requires measurement of thermal insulation and air permeability of the fabric.

EN 511 requires measurement of thermal insulation of the complete glove with a thermal hand model. It also requires measurement of contact resistance measured with a hotplate on a sample of the glove from the palm side. Results are presented in one of four classes.

12.7 Performance of clothing for cold protection

12.7.1 Standard values for clothing insulation

The standard value for clothing insulation of an ensemble is the basic insulation value (I_{cl}). According to the standards (ISO 9920, 1993; ISO 11399, 1995), this

Table 12.2 Basic insulation values (I_{cl}) of selected garment ensembles measured with a thermal manikin (modified from ISO/DIS 11079 (2004))

Clothing ensemble	m^2 °C/W	clo
1. Briefs, short-sleeve shirt, fitted trousers, calf length socks, shoes	0.08	0.5
2. Underpants, shirt, fitted trousers, socks, shoes	0.10	0.6
3. Underpants, coverall, socks, shoes	0.11	0.7
4. Underpants, shirt, coverall, socks, shoes	0.13	0.8
5. Underpants, shirt, trousers, smock, socks, shoes	0.14	0.9
6. Briefs, undershirt, underpants, shirt, overalls, calf length socks, shoes	0.16	1.0
7. Underpants, undershirt, shirt, trousers, jacket, vest, socks, shoes	0.17	1.1
8. Underpants, shirt, trousers, jacket, coverall, socks, shoes	0.19	1.3
9. Undershirt, underpants, insulated trousers, insulated jacket, socks, shoes	0.22	1.4
10. Briefs, T-shirt, shirt, fitted trousers, insulated coveralls, calf length socks, shoes	0.23	1.5
11. Underpants, undershirt, shirt, trousers, jacket, overjacket, hat, gloves, socks, shoes	0.25	1.6
12. Underpants, undershirt, shirt, trousers, jacket, overjacket, overtrousers, socks, shoes	0.29	1.9
13. Underpants, undershirt, shirt, trousers, jacket, overjacket, overtrousers, socks, shoes, hat, gloves	0.31	2.0
14. Undershirt, underpants, insulated trousers, insulated jacket, overtrousers, overjacket, socks, shoes	0.34	2.2
15. Undershirt, underpants, insulated trousers, insulated jacket, overtrousers, overjacket, socks, shoes, hat, gloves	0.40	2.6
16. Arctic clothing systems	0.46–0.70	3–4.5
17. Sleeping bags	0.46–1.4	3–9

value is measured with a standing, static manikin under still wind conditions. The basic insulation value is listed in most tables with information about clothing insulation, for example ISO 9920. Table 12.2 provides examples of clothing insulation values intended for cool to cold environments. Insulation increases with number of layers and thickness of clothing. Insulation is built up by air layers. Fabrics and textiles that trap air in layers and minimise internal convection insulate well. The chemical and physical properties of the fibres are less important, because the space they occupy in a fabric or textile is small. Also, in multi-layer ensembles the fabrics themselves may be less important than the intermediate air layers they create. A rough estimate is that fabrics on top of each other and battings provide about 1.5 clo/cm thickness, irrespective of fibre type.

In practical use the thermal properties of a clothing ensemble change dynamically as a result of the influence of, for example, body movements, wind and moisture accumulation. Such factors disturb the microclimate air layers and change the thermal properties. The basic insulation value, in practice, only applies to a standing person in still air. For use in evaluation of dynamic work conditions, corrections are required. This can be done in two ways:

- additional measurements are carried out with a thermal manikin
- the basic insulation value is corrected using empirical algorithms.

The first approach comprises measurements with a walking manikin under the influence of different air velocities. This provides realistic information about the performance of the tested ensemble, but only for the actual test conditions. This option is available in a European standard for cold protective clothing (ENV 342, 2003). The cost of testing quickly becomes high when the number of conditions increases. Manikins also are limited in terms of type, range and intensity of movements making them less suitable for simulating many sports activities.

The second approach requires one or more equations that correct the I_{cl} value for actual activity and climatic conditions (usually wind). One such model is included in the computer program for the revised IREQ-standard (ISO/DIS 11079, 2004).

12.7.2 Influence of walking and wind

Equations have been derived from experiments in different laboratories. Nilsson *et al.* (2000) investigated winter clothing ensembles in a climatic wind tunnel and proposed a correction equation taking into account walking speed, wind speed and air permeability of the outer layer fabric. Havenith and Nilsson (2004) added data from other sources and proposed a slightly modified equation:

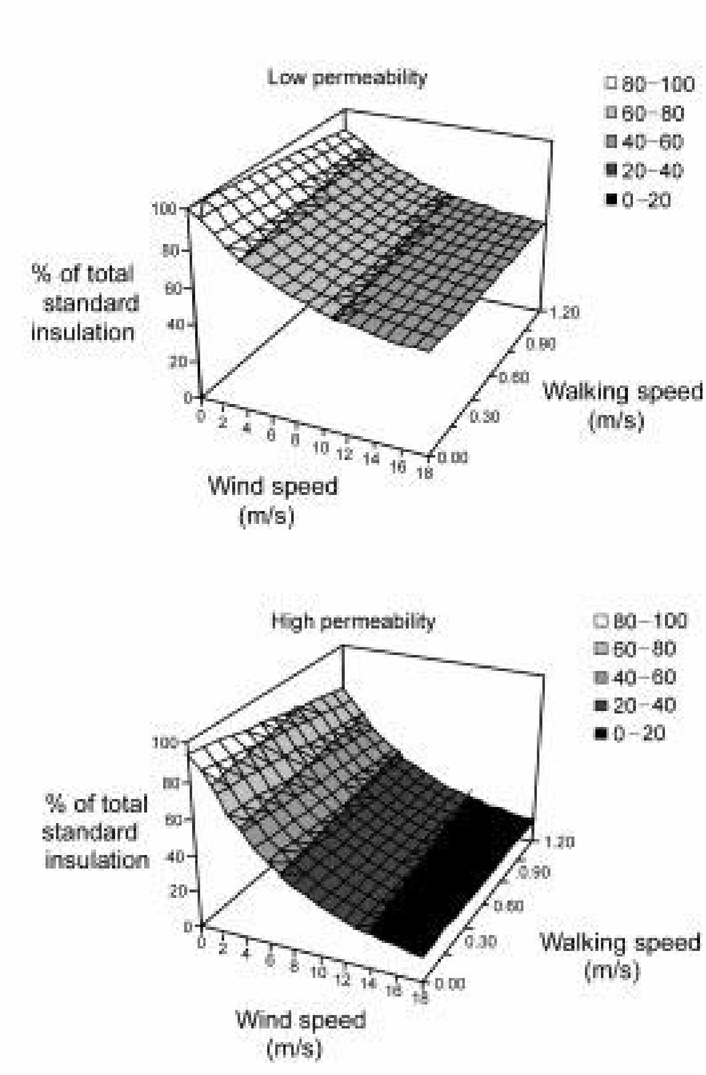
$$I_{T,r} = \left\lfloor e^{[-0.0512\cdot(v_{ar}-0.4)+0.794\cdot 10^{-3}\cdot(v_{ar}-0.4)^2-0.0639*w]p^{0.1434}} \right\rfloor \cdot I_{T,static} \quad (12.10)$$

where v_{ar} is the relative air velocity in m/s, w is the walking speed in m/s and p is the air permeability in l/(m^2 s).

The correction equation applies to the total insulation value and much of the effect on the boundary air layer is picked up and included. Figure 12.3 shows that also with an outer ensemble, which is highly windproof, the reduction in insulation is more than 30–40% at high wind speeds. Much of this reduction is due to reduced boundary air layer insulation as well as to compression effects on the wind side of the body.

The number and size of pores in the construction determine the air permeability of a textile. Textiles with no pores are impermeable and offer good protection against wind effects. However, materials with sufficiently small pores may, in practice, be almost impermeable to air penetration.

In some sports, significant sweating may be necessary to balance the high metabolic heat production. Wind enhances evaporative heat transfer and results



12.3 Effects of wind and walking speed on the thermal insulation of clothing. Effect is expressed as a percentage reduction of the values measured with a standing manikin in still air. Air permeability of the outer garment layer is 1 l/(m^2 s) (top panel) and 1000 l/(m^2 s) (bottom panel), respectively.

in additional cooling that is desirable in periods of peak performance. In breaks and in periods of low activity, however, windproof and insulative outer layers are required, reducing the additional cooling to balance the much lower heat production.

12.7.3 Influence of water and moisture

Clothing may get wet from precipitation or contacts from outside. Wetting from the outside should be prevented by selection of water-repellent or waterproof fabrics for the outermost clothing layer. A number of materials on the market are absolutely impermeable to water. Different treatments of fabrics render them more or less waterproof – a property, however, that may deteriorate with ageing and washing.

Clothing may also get wet from absorption and accumulation of sweat. This is likely to occur at high activity levels. In such circumstances the selection of outer layer must be a compromise between the need for wind protection and the need for additional evaporative cooling.

Some microporous materials and even treatments of fabrics comprise high levels of waterproofness (and windproofness). In addition, they may allow the passage of water vapour ('breathability'). This combination of properties results in garments that are waterproof (and windproof) yet breathable in the sense that a limited amount of evaporated sweat may pass from the skin to ambient air. These features may be of relevance in temperate and warm climates. In the cold, however, a physical phenomenon limits the function.

In the cold there is a steep temperature gradient from skin, across clothing layers to ambient air. The dew point temperature and eventually also the freezing temperature may be reached inside the clothing by the moist air passing from the skin. Condensation occurs and moisture builds up in discrete layers. Wetting of clothing reduces the effective thermal insulation (Holmér, 1985; Meinander, 1994; Meinander and Subzerogroup, 2003).

Four winter ensembles were measured during three hours with a sweating thermal manikin at two sweating rates, 100 and 200 g/h/m^2, respectively. The air temperatures varied from 0 to −40 °C. Table 12.3 shows the accumulated water during the three hours and the associated reduction in effective insulation (Meinander and Subzerogroup, 2003). It is readily shown that sweat evaporation

Table 12.3 Actual evaporation and difference in total thermal insulation as result of sweating and sweat accumulation

Ensemble	Total dry insulation	Sweating rate 100 g/h/m^2		Sweating rate 200 g/h/m^2	
		Evaporation	Insulation reduction	Evaporation	Insulation reduction
	m^2 °C/W	%	%	%	%
Ens. 1 at 0 °C	0.32	54	0	61	−7
Ens. 2 at −10 °C	0.46	48	−13	38	−21
Ens. 4 at −25 °C	0.64	17	−21	17	−28
Ens. 4 at −40 °C	0.65	21	−20	15	−21

reduces significantly in the cold. At −10 and −25 °C about 40–60% of sweat evaporates. At lower temperatures, evaporation is less than 20%.

At very high activity levels the insulation requirement, as mentioned, is very low (Fig. 12.1) and clothing is made up of one to two layers of thin, body-tight layers. Under such circumstances the temperature of the surface of clothing is maintained well above freezing temperatures, allowing more passage of water vapour from the skin and evaporative cooling. This phenomenon is sometimes clearly visualised by a cloud of steam surrounding, for example, a cross-country skier when he arrives and stops in the finish area.

12.7.4 Effects of solar radiation

Solar radiation in the cold may improve heat balance. Dark colours absorb more radiative heat of the visible spectrum than do light colours (Nielsen, 1991). However, due to the many layers normally worn on a cold day the net effect of heat absorption on the outermost layer is likely to be small.

12.7.5 Effects of treatment

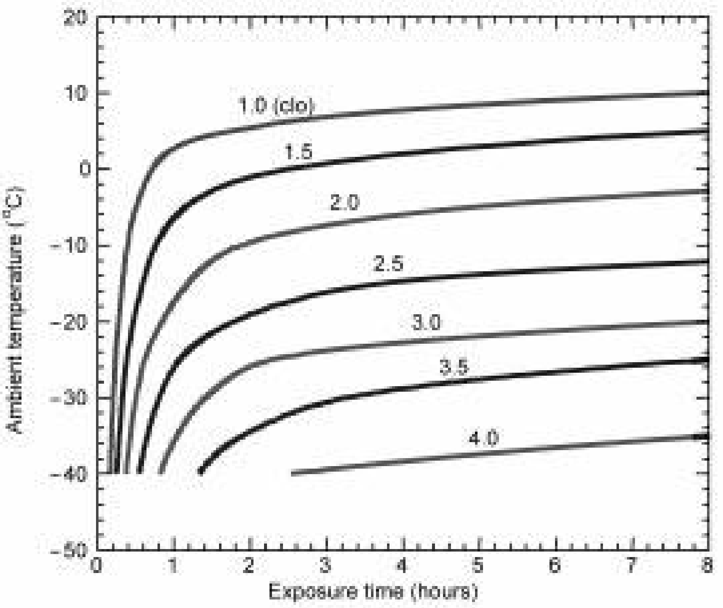
Many properties of textiles and clothing deteriorate with wear and washing. Surface treatments are likely to gradually disappear and must be reapplied. This is particularly true for treatments against water permeation. Thermal insulation may reduce after repeated washing. The magnitude depends on many factors such as quality, type and properties of fibres and textiles, shrinking and type of construction. Thick, insulative garments and sleeping bags have been reported to lose up to 20% in thermal insulation after washing.

12.7.6 Prediction of protection

As previously mentioned, the conditions for heat balance can be described by a heat balance model (ISO/DIS 11079, 2004). The model allows the determination of:

- required clothing insulation (IREQ) for given combinations of activity and climate
- exposure times for acceptable cooling for a defined clothing insulation for combinations of activity and climate
- wind and motion effects on thermal insulation and heat balance.

The input values for the model are ambient climatic conditions (air temperature, mean radiant temperature, wind speed and humidity) and activity level for IREQ. The other two analyses require a basic insulation value to be defined for the actual clothing ensemble. ISO/DIS 11079 (2004) lists a computer program that performs the necessary calculations. The program is available online (ThEL-Lund, 2005).



12.4 Exposure time and at different combinations of ambient temperature (still air) and clothing insulation for light activity (110 W/m^2). Clothing insulation is given as the basic insulation value (see text and Table 12.2). The value is automatically corrected for wind and walking speed in the computer program (ISO/DIS 11079, 2004).

Figure 12.4 shows the protective value of clothing ensembles at nominal insulation values of 1–4 clo at a light work intensity corresponding to a metabolic rate of 110 W/m^2. The clo values are basic values that can be taken from, for example, Table 12.2. When the available insulation value is insufficient, a recommended exposure time is calculated. Values in Fig. 12.4 apply to still air. All curves will shift to the left (shorter exposure times) with increasing wind and walking speed (compare with Fig. 12.3).

The IREQ model is most suitable for activities in which heat losses can be controlled by adjustment of clothing and number of layers (convective and radiative heat loss). At very high activity levels, sufficient heat loss cannot be maintained due to the requirement for minimal clothing for the prevention of local skin cooling. This minimal clothing, often comprising thin underwear and a windproof, thin outer layer, must be chosen so that it allows sufficient water vapour transfer for evaporative cooling. These conditions are characterised more by heat stress than by cold stress and require a more detailed modelling of clothing heat transfer than provided by the IREQ model.

It can be shown that water vapour resistance is affected by walking and wind, and furthermore, that these two factors greatly enhance evaporative heat transfer. The relation is based on data for temperate and warm environments. It is likely that the effect is less pronounced, but still significant, in cold environments, in particular for light, one- to two-layer clothing.

12.8 Specific materials and textiles for cold protection

12.8.1 The multi-layer principle

As previously mentioned, protection against cold is determined by the thickness of still air layers covering almost all parts of the body surface. Accordingly, all kinds of textiles and materials may be used, provided this principle is adhered to. Typically, a cold protective ensemble is built up by several layers of garments on top of each other. The layers, apart from contributing to the total insulation, serve specific purposes.

The inner layer is worn directly on top of the skin and controls the microclimate temperature and humidity. With low activity the layer must reduce air movements. With high activity, heat and moisture should be transported from the layer to cool the skin. Moisture control can be performed by absorption, by transportation to the next layers or by ventilation. Absorption reduces skin humidity and retains relative comfort, but moisture remains in the clothing system and may be detrimental to heat balance at a later stage. Using hydrophobic textiles next to skin quickly increases humidity, and moisture is transferred to outer layers. The advantage is an increased awareness of heat imbalance (discomfort), but moisture remains in the clothing system. The ventilation principle requires a vapour barrier worn next to skin. Microclimate humidity quickly rises with sweating, but water vapour cannot escape to outer layers. The humid microclimate forces the wearer to open up the clothing and ventilate the microclimate. This principle is preferably used in resting and low-activity conditions.

The absorbing technique may be useful for low to moderate activities with limited sweating. The transporting principle may be applied to all kinds of activities, but in particular for high activity with sweating. They are most suitable for sports events and long-term exposure.

Another important factor for cold protection is moisture control. This means that wetting of layers must be avoided at all times (from inside by sweating or from outside by rain or snow). If this is not possible, the consequences of moisture accumulation must be controlled.

The middle layer provides most of the insulation. It comprises one or several garments of thicker material depending on the requirements. Choice of textiles is more or less arbitrary as long as good insulation is provided. Non-absorbing materials should be selected for long-term exposure with limited heating and drying opportunities (expeditions, etc.).

The outer layer must provide protection against environmental factors such as wind, rain, fire, tear and abrasion. In occupational contexts, protection may also be required against, for example, chemical and physical agents. This layer can also add to the total insulation by the provision of insulation liners and battings.

12.8.2 Natural and synthetic fibres

Textiles such as wool and wool blends possess a high absorbing capacity and can handle small amounts of moisture without losing their insulation properties. Wool can be used as a next-to-skin fabric and may keep the skin relatively dry. When the fabric becomes saturated, however, the moisture control is reduced. Cotton is absorbing as well, but clings to skin when wet and should not be close to the skin in cold environments. Many synthetic textiles are hydrophobic and the moist air moves from skin through the fabric to the next layer. The skin microclimate quickly becomes humid during sweating. This humidity is uncomfortable and causes the wearer to make appropriate adjustments. This is also the main effect and purpose of using vapour barrier fabrics next to skin.

Moisture absorbed in garments, in addition to causing discomfort at some stage, adds to the carried weight by the person. In addition, it gradually reduces thermal insulation of that particular layer. When activity drops and sweating ceases, the drying of wet clothing layers may deprive the body of more heat than is generated by metabolic rate. The result is a post-chilling effect that may endanger heat balance and result in hypothermia.

As long as one can stay dry, the choice of material (natural or synthetic) for the various layers is a matter of taste or other preferences and requirements. With sweating and, in particular, with longer outdoor excursions, the advantage of lightweight, strong and hydrophobic materials as part of the clothing ensemble should be recognised.

12.8.3 Improved insulation

Wool and down fabrics are highly insulative due to the very nature of the fibre materials. Modern synthetic textiles such as battings made of polyester hollow fibres or polyolefin microfibres resemble in a way the natural materials and provide good insulation per unit thickness.

As a spin-off to the space technology, reflective materials (mostly aluminised fabrics or fibres) are used in garments and survival kits. The idea is that much of the heat the body loses through radiation will be reflected back to skin. Such an ensemble will transmit less overall heat and the net insulation is higher compared with a similar one without a reflective layer. Practical tests, however, have shown that the net effect is small – in certain conditions negligible. The reasons are several. Radiation heat loss is only a minor part of the overall heat loss in the cold, in particular in the presence of wind and/or body movements

(10–15%). Reflection of radiation requires spacing of layers, which is difficult to achieve and maintain. Most reflective fabrics are impermeable and interfere with moisture transfer. Aluminised insoles for shoes are common but provide no additional insulation compared with soles of similar thickness without aluminium. Gloves and socks with aluminium threads in the fabric do not give higher insulation compared with those without.

12.8.4 'Breathing fabrics'

In foul weather, good protection against rain and snow is required. However, waterproof fabrics may interfere with evaporative heat exchange. During activity the person gets wet from inside instead of from outside. Microporous materials help to solve this problem to some extent. The small pores allow water vapour to pass but stop liquid water. This works reasonably well in temperate and warm climates. Due to the 'cold wall' principle, these fabrics become less valuable in colder climates. During intermittent cold and warm exposures (in and out), they may allow absorbed moisture to escape in the warm conditions. Also, textiles of this kind are often highly windproof, which is beneficial in cold environments.

12.8.5 Intelligent textiles

In recent years several new types of materials and fabrics have been put on the market that contain some active component. Examples are phase-change materials (PCM), inflated tubings and electrical heating.

Fabrics containing PCM respond to cooling by releasing heat from a range of waxes in the fibre or fabric (fibre content changes from solid to liquid phase). Once solid it reacts to heating by absorbing heat (fibre content melts). By choosing a certain temperature for the phase change, the fabric (in a garment) could assist the wearer's thermoregulatory adjustment to hot and cold environments. Although the principle is physically sound (compared with the industrial ice-vest), the PCM fabrics on the market contain insufficient amounts of the phase-change material. The heat transfer involved is almost negligible, difficult to measure and almost impossible to perceive (Weder and Hering, 2000; Shim *et al.*, 2001; Ying *et al.*, 2003).

Inflatable fabrics should, in principle, allow the expansion of thickness of the ensemble, thereby increasing the effective insulation. Fabrics with a system of thin tubings can be inflated by the mouth. The effect is a thicker layer of that particular garment, which should add insulation.

Electrically heated elements incorporated into fabrics have been available for many years. The disadvantage, so far, has been the low capacity of portable batteries, and the durability of the wiring system. The rapid development of mobile phones and portable computers has resulted in the availability of powerful, long-lasting, portable batteries that can be used also for auxiliary heating. This concept is likely to be most beneficial to the heating of hands and feet, but garments are already available on the market that have built-in batteries and are charged from the mains supply.

12.9 Clothing for sports

The same basic principles apply to clothing for sports as for any other clothing (Gonzalez, 1988). The main difference relates to the extreme requirements in certain conditions.

12.9.1 Endurance sports

Cross-country skiing or skating for hiking purposes is associated with high levels of metabolic heat production. Also, under rather cold conditions, the problem is often too much rather than too little clothing. For the hiker it is important to adjust clothing to a level that provides comfortable skin temperatures yet avoids sweating that may wet clothing and endanger heat balance in periods of low activity. Hands and head can be used as radiators, in order to suppress sweating. The drop in local skin temperatures, however, may limit their use. Extra clothing must be carried to improve protection during breaks and periods of low activity or when the weather deteriorates.

Competitive cross-country skiing is often a question of heat stress rather than cold stress. Extremely high activity levels produce large amounts of metabolic heat that in many circumstances cannot be dissipated at a high enough rate. Although significant sweating and evaporation take place in addition to convection and radiation, overheating may occur, and body core temperature increases. The clothing requirement is minimal in order to facilitate heat dissipation. The skin, however, must be covered by at least one clothing layer in order to prevent uncomfortable local skin cooling. This is particularly valid for torso, arms and legs. Hands and head cooling are more tolerated (within certain limits) and can often remain unprotected. Owing to sweat accumulation in clothing, convective cooling gradually increases. Ideally, underwear should be made of hydrophobic fibre materials that have little or no moisture absorption capacity. It may be necessary to optimise the outer layer of a thin garment in terms of air and vapour permeability and moisture absorption properties. The front part of the garment may be windproof, whereas the back part is more porous and vapour permeable. Fabrics of synthetic fibres are more likely to meet the requirements for protection and more easy to handle in high-activity sports.

12.9.2 Alpine skiing

Alpine skiing must be regarded as an intermittent sport with periods of intense activity (skiing) alternating with periods of low activity (lift). Some forms of alpine skiing involve climbing mountains for minutes or even hours, carrying skis, followed by a long period of downhill skiing. Clothing for intermittent exercise must be flexible and allow adjustments as well as change of garments. Uphill walking is extremely energy consuming and produces large amounts of heat. Clothing must be thin and light, eventually windproof. Hands and head may be bare to improve heat loss. Also, downhill skiing produces heat, because of the storage of released potential energy in working muscles. Speed and wind, however, accelerates heat losses and necessitates more clothing and windproof outer layers. In some conditions, for example at high altitude in ‘summer’ conditions, sunshine may add radiation heat, particularly with dark-coloured fabrics, requiring another adjustment of clothing.

12.9.3 Low- and medium-activity sports

Some types of sport are characterised by low activity and long periods of sitting or standing, for example fishing, shooting and watching sports events. This is a simple case in terms of predicting requirements, but difficult to solve in practice. As illustrated in Fig. 12.1, the insulation requirements at low temperatures are very high: 4–6 clo. This level is not available with everyday winter clothing. The best available clothing systems on the market provide 3–4 clo (see Table 12.2). Several layers, evenly distributed over the body surface are required. Feet and hands need highly insulative gear that is well sealed with arms and lower legs. Similarly, the head and neck must be well protected and sealed with torso clothing. The head alone, unprotected, may lose more than 50% of metabolic heat production at rest in very cold environments. Nevertheless, heat balance cannot be maintained by passive clothing and exposure needs to be terminated after some time (see Fig. 12.4). Behavioural and/or technical measures are needed to extend exposure. Intermittent periods of higher activity would restore heat balance. Auxiliary heating with electrical or chemical equipment or a simple fire would also help to reduce cooling and extend exposure time. Cooling by conduction to cold surfaces, for example ice, packed snow or cold seats, must be avoided through appropriate seat covers made of incompressible, insulative material (e.g. neoprene).

Spectators at sporting events can often take advantage of the shielding effect of crowding. By standing or sitting close together, the microclimate improves and reduces overall heat losses.

Skiing and skating at moderate pace (for example, in groups of different skills and abilities) offers easier conditions for the maintenance of heat balance. Metabolic heat production is reasonably high to allow relatively light clothing also at low temperatures (see Fig. 12.1). This means underwear and an outer layer providing protection against the wind (if needed). Sweating can be controlled and minimised. Underwear can be of made of synthetic, non-absorbing fibres, although absorbing fibres such as wool and wool blends, may also be used. The small amounts of moisture may be readily absorbed in such materials without deterioration of their insulating properties. Cotton fabrics are not recommended because they lose insulation as they become wet, and they cling to the skin.

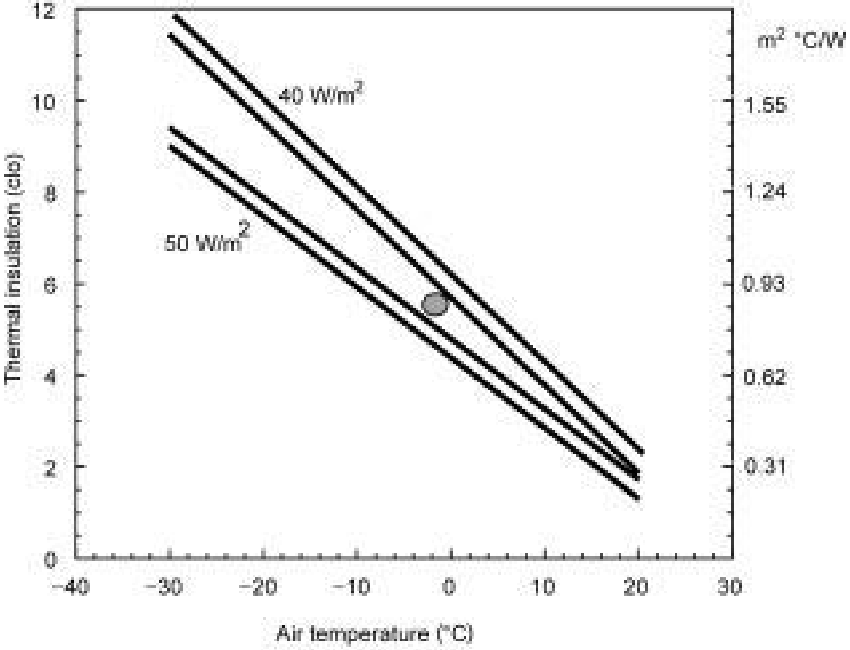
12.9.4 Sleeping outdoors

Sleeping outdoors is the ultimate challenge in terms of cold exposure and represents the extreme of low-activity exposure. The problem, however, is more often manageable than one would expect. In most circumstances a tent or a hut (for example an igloo) is raised. The microclimate inside the shelter will be much warmer than outside and, in particular, the wind cooling effect is eliminated. Backpackers use neoprene sheets as mattresses. Also, inflatable mattresses are available, providing protection against the cold ground. Additional ground cover in the form of leaves, branches, fur, etc., improve ground insulation. A sleeping bag, selected on the basis of the environmental requirements, may readily provide sufficient protection even at very low outdoor temperatures (−30 to −40 ºC). The microclimate in the shelter may become 10–20 ºC higher than outside, as a result of the person's own body heat. Sleeping bags (single or double bag) are available that provide insulation values as high as 10–12 clo.

The igloo hotel in Jukkasjärvi in the very north of Sweden is a world famous tourist attraction. People overnight in the hotel that is completely made of ice and snow. The temperature in the rooms is just below 0 ºC. Suitable mattresses and sleeping bags provide conditions for good heat balance, sleep and an exotic experience. Figure 12.5 shows the insulation requirement for sleeping in a cold, wind protected shelter. The dot at −1 ºC shows the result of a study of 46 persons that slept one particular night in the Jukkasjärvi igloo hotel. The standard sleeping bag that was used by all subjects provided 5.5 clo and the average temperutre during the night was −1 ºC. The average response of the subjects was that they felt neutral to slightly warm during the night. This is in line with the expected requirement. The point falls between the two levels of metabolic rate that would be expected for sleeping persons. It must be mentioned, however, that the individual variation was large. People are different and there must be room for individual adjustment also to this kind of standard, cold environment.

12.9.5 Water sports

Although most people prefer to enjoy water sports in temperate and warm weather conditions, some sporting events take place in waters at temperatures well below 20 ºC and sometimes as low as 5 ºC. Long-distance swimming (e.g. crossing the English Channel) is a challenge not only to the swimming capacity, but also to body heat balance even at 'normal' temperatures around 20 ºC. One



12.5 Thermal insulation requirements for sleeping to provide heat balance during sleep at low temperatures. The dot refers to the results of a study on 46 persons sleeping in a standard sleeping bag of 5.5 clo at −1 °C. For further explanations see text.

of the most effective protective measures is to build up a thick, subcutaneous fat layer. This 'internal clothing' may allow swimming in extremely cold waters. Covering the skin surface with grease adds little insulation. However, a well-designed wetsuit of neoprene greatly enhances the cold protection and also allows thinner persons to participate in events such as the triathlon. Triathlon includes distance swimming as one of the three events.

Windsurfing and sailing may result in more or less complete exposure to cold water. Wetsuits, but also insulating, well-sealed drysuits, provide good protection and allow extended exposure both above and in the water.

12.10 Sources of further information

Several international conferences have focused on clothing, climate and protection:

- Problems with cold work (Holmér and Kuklane, 1998)
- Nokobetef 6 and 7 organised together with the 1st and 2nd European Conference for Protective Clothing (ECPC) (Richards, 2003; Kuklane and Holmér, 2000)

- Environmental Ergonomics Conferences (Holmér *et al.*, 2005).

There are several fibre and textile conferences that provide valuable information.

12.11 References

Breckenridge, J. R. & Goldman, R. F. (1977) Effect of clothing on bodily resistance against meteorological stimuli. In Tromp, J. (ed.) *Progress in Human Biometeorology*. Amsterdam, Sweits & Zeitlinger.

EN 511 (2004) *Protective gloves against cold*. Comité Européen de Normalisation.

ENV 342 (2003) *Protective clothing – Ensembles and garments for protection against cold*. Comité Européen de Normalisation.

ENV 343 (1998) *Protective clothing – Protection against foul weather*. Comité Européen de Normalisation.

ENV 14058 (2002) *Protective clothing – Garments for protection against cool environments.* Comité Européen de Normalisation.

ENV 14360 (2002) *Protection against foul weather – Test method for the rain tightness of a garment: Impact from above with high energy droplets*. Comité Européenne de Normalisation.

Gagge, A. P., Burton, A. C. & Bazett, H. C. (1941) A practical system of units for the description of the heat exchange of man with his environment. *Science*, 94, 428-430.

Gonzalez, R. R. (ed.) (1988) *Biophysics of Heat Transfer and Clothing Considerations*. Brussels, U.S. Army Research Institute of Environmental Medicine.

Havenith, G. & Nilsson, H. (2004) Clothing evaporative heat exchange in comfort standards. *European Journal of Applied Physiology*, 92(6), 636–640.

Holmér, I. (1985) Heat exchange and thermal insulation compared in woollen and nylon garments during wear trials. *Textile Research J.*, 55, 511–518.

Holmér, I. (2004) Thermal manikin history and applications. *European Journal of Applied Physiology*, 92(6), 614–618..

Holmér, I. & Kuklane, K. (1998) *Problems with cold work*. Arbete & Hälsa 18, NWL, Stockholm, Sweden, 272.

Holmér, I., Kuklane, K. & Gao, C. (2005) *Environmental ergonomics XI*, Lund University, Sweden, 663.

ISO 5085-1 (1989) *Textiles – Determination of thermal resistance – Part 1: Low thermal resistance*. International Standards Organisation.

ISO 8996 (2004) *Ergonomics – Determination of metabolic heat production*. International Standards Organisation.

ISO 9920 (1993) *Ergonomics – Estimation of the thermal characteristics of a clothing ensemble*. International Standards Organisation.

ISO 11092 (1993) *Textiles – Physiological effects – Measurement of thermal and water-vapour resistance under steady-state conditions (sweating guarded hotplate test)*. International Standards Organisation.

ISO 11399 (1995) *Ergonomics of the thermal environment – Principles and application of International Standards*. International Standards Organisation.

ISO 15831 (2003) *Thermal manikin for measuring the resultant basic thermal insulation*. International Standards Organisation.

ISO 20811 *Textiles – Determination of resistance to water penetration*. International

Standards Organisation.

ISO EN-9237 *Textiles – Determination of permeability of fabrics to air*. International Standards Organisation.

ISO/DIS 11079 (2004) *Ergonomics of the thermal environment – Determination and interpretation of cold stress when using required clothing insulation (IREQ) and local cooling effects*. International Standards Organisation.

Kuklane, K. & Holmér, I. (2000) *Ergonomics of protective clothing*. Arbete & Hälsa, NWL, Stockholm, Sweden, 313.

McCullough, E. (2001) Interlaboratory study of sweating manikins. *5th European Conference on Protective Clothing and NOKOBETEF 7*. Montreux, Switzerland, EMPA.

Meinander, H. (1994) Influence of sweating and ambient temperature on the thermal properties of clothing. Fifth International Symposium on Performance of Protective Clothing Improvement through Innovation. San Francisco.

Meinander, H. (2000) Extraction of data from sweating manikins tests. In Nilsson, H. & Holmér, I. (eds) *Thermal manikin testing 3IMM*. Stockholm, National Institute for Working Life.

Meinander, H. & Subzerogroup (2003) *Thermal Insulation Measurements of Cold Protective Clothing using Thermal Manikins*. Technical Research Center, Tampere, Finland.

Newburgh, L. H. (ed.) (1949) *Physiology of Heat Regulation and the Science of Clothing*. Philadelphia, W. B. Saunders Company.

Nielsen, B. (1991) Solar heat load on clothed subjects. *Proceedings of 2nd International Symposium on Clothing Comfort Studies in Mt. Fuji*. Fuji Institute of Education and Training, Japan, The Japan Research Association for Textile End-uses.

Nilsson, H. O., Anttonen, H. & Holmér, I. (2000) New algorithms for prediction of wind effects on cold protective clothing. *1st European Conference on Protective Clothing and NOKOBETEF 6*. Norra Latin, Stockholm, Sweden.

Richards, M. (2003) Challenges for protective clothing. Second European Conference on Protective Clothing, Montreux, Switzerland, EMPA.

Shim, H., McCullough, E. & Jones, B. (2001) Using phase change materials in clothing. *Textile Res. J.*, 71, 495–502.

ThEL-Lund (2005) *www.eat.lth.se/Research/Thermal/Thermal_HP/Klimatfiler/IREQ2002alfa*.

Umbach, K. H. (1992) Prediction of the physiological performance of protective clothing based on laboratory tests. In Mäkinen, H. (ed.) *NOKOBETEF IV: Quality and usage of protective clothing*. Kittilä, Finland.

Weder, M. & Hering, A. (2000) *How Effective are PCM Materials? Experience from laboratory measurements and controlled human subject tests*. St. Gallen, Switzerland, EMPA.

Ying, B., Kwok, Y., Li, Y., Yeung, C. & Song, Q. (2003) Thermal regulating functional performance of PCM garments. *Int. J. Clothing Science and Technology*, 16, 84–96.

13

Water resistance and water vapour transfer

Dr J E RUCKMAN, Manchester Metropolitan University, UK

13.1 Introduction

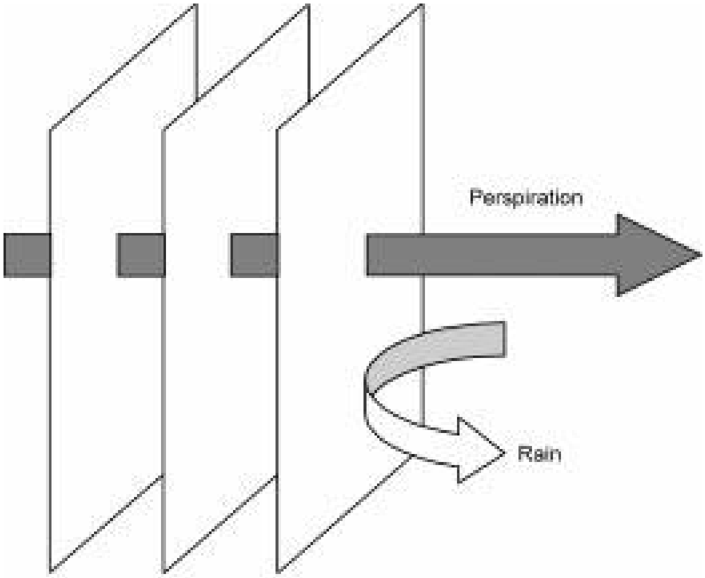
A recent market research study shows that the number of people engaged in outdoor sports is on the increase and that sales of sports clothing, especially for outdoor sports, are also increasing. Outdoor sports are normally participation and not spectator sports, and it is often the case that those involved in such sports require protection from unexpected rain or snow. The categorisations of outdoor sports that are normally used by UK sportswear retailers, and examples of specific sports included within these categories, are: (1) high mountain, including mountaineering, expedition, alpine climbing, UK winter climbing, ice climbing, ski mountaineering, snow sports such as snowboarding; (2) multi-activity, including climbing, biking/cycling, running, adventure racing; and (3) hill walking/backpacking, including hill walking, rambling, fell walking, hiking, scrambling, backpacking.

There are also outdoor sports which require protection not only from the rain but also from water. These include water sports such as wind surfing, canoeing and kayaking, where a person experiences direct contact with water, and also offshore sports and activities such as yachting. Golf may also be categorised as an outdoor sport, since keen golfers, anxious to play all year round in the UK, have to face wet, windy and cold conditions.

The reason why people engage in and enjoy outdoor sports is the excitement of the various activities that they can pursue under various environmental conditions. Since both the environment and the heat generated by activities are beyond the control of the person engaged in the outdoor sports, it is important to provide people with sportswear that provides both protection from the environment and comfort to maximise their enjoyment. The outdoor sportswear developed and manufactured for various activities to be undertaken in various environmental conditions forms a ‘clothing system’ that normally comprises three layers of clothing: a base liner, a mid layer and an outer layer. The base liner of a clothing system is designed to wick the sweat and delay the onset of chilling. The mid layer is designed to keep the wearer warm by trapping and storing warmed air. The outer layer provides protection for all the other layers and the body.

For complete protection from rain or water it is possible to wear a clothing system incorporating a completely waterproof outer layer; however, the use of a simple waterproof outer layer is ineffective because moisture from sweating that is generated due to sports activities will collect in the clothing system, and the quantity of moisture generated inside the clothing system by sweating can be as if the outer layer had leaked. This not only results in a loss of insulation, but also leads to excessive evaporation cooling when the waterproof layer is removed. The ideal properties required for a three-layer clothing system, therefore, include both protection and comfort requirements and the system needs to be waterproof but water vapour permeable, as illustrated in Fig. 13.1.

Waterproof fabrics for use in the outer layer of a clothing system for total protection have been around for a considerable time. The first waterproof fabrics, cotton Ventile fabrics, were introduced during the 1930s and 1940s. In outdoor sportswear, however, since it is important to prevent condensation occurring on the inside of the sportswear, the textile industry has attempted for some years to produce a fabric that is truly waterproof but allows perspiration to escape through the fabric. Such 'breathable' fabrics, believed to have been first developed by W. Gore & Associates, have undergone significant development since the first Gore-Tex fabric was launched in the US in 1976 (Ward, 1998). Since then there have been many developments in these fabrics that have been termed 'waterproof breathable' fabrics.



13.1 Requirements for outdoor sportswear.

From the point of view of the mechanisms of waterproofness and breathability, waterproof breathable fabrics can be categorised into three types: densely woven fabrics; fabrics with laminated or coated microporous film (microporous fabric); and fabrics with laminated or coated hydrophilic film (hydrophilic fabric). The following are brief explanations of these three types. Detailed discussion of other types of coated and laminated fabrics used in sportswear and their properties are provided elsewhere in this book.

The foremost densely woven types of fabrics are Ventile fabrics and microfibre fabrics. Ventile fabrics are woven from pure cotton and low-twist yarns in a plain weave. When they are in a dry state, the pores between the weft and warp yarns are relatively large. When rainfall or water initially wets the fabric, the cotton yarns swell and constrict the inter-yarn pores. The property balance between the waterproofing and breathability of Ventile fabrics varies with the swelling of cotton yarn. Microfibre fabrics are tightly woven using synthetic microfilament yarn. This type of fabric does not use the swell mechanism, but the interstices between yarns in the fabrics are small enough to repel water whilst allowing water vapour to escape.

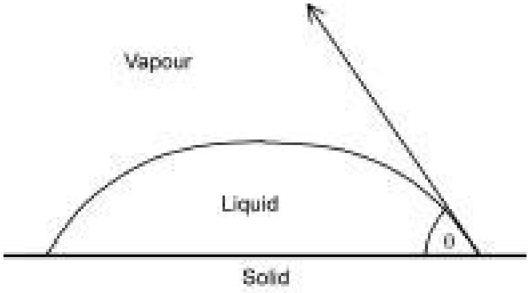
Microporous fabrics also use the mechanism of difference in size between water droplets and water vapour molecules in the same way as densely woven fabrics. However, microporous fabrics use a film with a microporous structure and rely on the many tiny holes within the film laminated or coated onto the fabric. Microporous fabrics include fabrics such as PTFE laminated fabrics and polyurethane laminated fabrics. The microporous structure is capable of transmitting water vapour at high rates.

The mechanism of water vapour transfer for hydrophilic fabrics is entirely different from the densely woven fabric and microporous fabric. Hydrophilic membranes are very thin films of chemically modified polyester or polyurethane containing no holes. The solid film laminated or coated onto a fabric incorporates an active component, such as polyethylene oxide (PEO), which typically comprises up to 40% by weight of the film (Lomax, 1991). Hydrophilic fabrics have a lower water vapour transfer rate than microporous fabrics under dry conditions. However, the water vapour transfer rate of hydrophilic fabrics increases significantly when the fabric is very near water, or the water vapour concentration between the skin and the fabric is very high.

In this chapter only the water resistance and water vapour transfer properties of waterproof breathable fabrics used as outer layers of outdoor sportswear will be discussed.

13.2 Water resistance

The water resistance of textiles normally refers to two separate properties: the water shedding property and the property of resistance to penetration by liquid water under pressure. Both properties are determined by the structure of the



13.2 Contact angle.

surface and the contact angle of water against the fibre or other solid material of which it is composed.

The contact angle is the angle that is formed at the edges of the water droplets where the water–air surface makes contact with the solid surface, as shown in Fig. 13.2. Thomas Young has outlined the relationship between the contact angle and the relative values of the adhesion of the liquid to solid and the liquid's cohesion to itself. If the adhesion of the liquid to the solid is equal to or greater than the cohesion of the liquid, the contact angle is zero and there is complete wetting; if the adhesion between liquid and solid is less than the cohesion of the liquid, then there is a finite angle, which increases as the adhesion of liquid to solid decreases relative to the cohesion of the liquid. The water resistance can be determined from Young's equation as follows (Moilliet, 1963):

$$W_{SL} = \gamma_L(1 + \cos\theta) \tag{13.1}$$

where W_{SL} is the work of adhesion between liquid and solid, γ_L is the average free energy of the liquid for unit area, and θ is the contact angle.

All textiles used in the outer layer of outdoor sportswear have had waterproofing applied to achieve water resistance. Since all textile materials are porous, containing many fine capillaries, waterproofing of the textiles requires the maximum possible resistance to penetration of water into the capillaries. Therefore a large contact angle with the walls of the capillaries is desirable (Moilliet, 1963; Kissa, 1984).

To determine the water resistance of waterproof breathable fabrics, appropriate tests for water resistance are required. The test methods may be divided roughly into two types: (1) tests which give information on the resistance of the fabric to surface wetting or penetration into but not through the fabric, and (2) tests which give information about the resistance of the fabric to penetration by rain. The tests which give information on resistance to surface wetting involve a simulated rain tester such as the Bundesmann rain tester, WIRA shower tester, the Credit rain simulation tester for seams, or AATCC rain tester. The tests which give information about resistance to penetration involve penetration pressure tests such as the hydrostatic head tester.

All waterproof breathable fabrics tend to perform exceedingly well under conditions of simulated rain tests. Work carried out by the UK Defence Clothing and Textile Agency (Scott, 2000) on a wide range of waterproof breathable fabrics generated general comparisons of fabrics in relation to water resistance. PTFE laminated fabrics demonstrated the greatest waterproofness whilst microfibre fabrics demonstrated the least waterproofness. Both porous polyurethane laminated fabrics and hydrophilic fabrics are positioned in between.

In a waterproof breathable outer layer, however, resistance to the penetration of water through the fabric, as measured by the hydrostatic head tester, is perhaps more important than the resistance to the penetration of water into the fabric, as tested in the rain simulator. It is believed that, to cover all circumstances and rigours encountered in use, an acceptable resistance to water pressure is in the order of 2 metres or higher of water column tested by hydrostatic head as described in BS 3546.

According to Keighley (1982), hydrostatic head test results for PTFE laminated fabrics and polyurethane coated fabrics achieved water entry pressure of 35 metres, and Parys (1994) reported that some laminates can support a column of more than 5 meters. Uedelhoven and Braun (1991) built a modified hydrostatic head apparatus to enable the testing of breathable materials under pressure loading. They tested 24 materials, including PTFE and polyester membranes as single-layer membranes and in two- and three-layer constructions, and polyurethane coatings. It was found that the microporous PTFE membranes had the highest pressure resistance of over 20 metres and the polyurethane materials had the lowest at 5 metres. However, they concluded that hydrostatic penetration resistance depends not only on the membrane material but also, and especially, on the construction of the finished garment.

It is true that, to meet the essential requirements of waterproofness of outdoor sportswear made of waterproof breathable fabrics, it is important to utilise not only these waterproof breathable fabrics but also an appropriate design and highly engineered sportswear manufacturing methods so that the sportswear maintains its waterproofness and durability during wear. Primary research with consumers indicated that the failure of performance of outdoor sportswear is initiated mainly by failure of the seams, as general wear and tear can quickly degrade the seams and threaten the performance of their waterproofness and durability. To achieve the maximum waterproofness of the seams, two aspects need to be considered: the type of the seams, together with type of thread used in the garment, and the method of sealing the constructed seams.

Amongst the numerous combinations of seam configurations found in outdoor sportswear, the most popular seams used for the outer layer seem to be plain seam (BS 1.01.01) and welted seam (BS 2.04.03). The most common stitch types employed to produce the seams are the lockstitch (BS 301) and the chainstitch (BS 401) for general sewing. The combination stitch (BS 401.504) is also sometimes used. Traditionally, cotton sewing threads were used for water-repellent garments; however, cotton covered core-spun polyester threads have replaced cotton sewing threads for better performance. Water-repellent finished threads are also available; however, manufacturers are reluctant to use water-repellent finished threads due to cost, the problem of colour matching to the garment, and retention of water repellency during laundry.

Sealing the sewn seam is an extremely important process in the making up of outdoor sportswear in relation to waterproofness. It has been observed, however, that some manufacturers of outdoor sportswear do not seal all the seams but restrict sealing to the seams which receive the greatest threat of water penetration, such as shoulder seams and side seams. It has been noted that some manufacturers of waterproof breathable fabrics insist on using a specific type of tape specially developed for their own branded fabrics to avoid the failure of the seams and to ensure the quality of a garment. The most popular seaming method currently used is the application of a heat-seal tape to the seam by hot air welding. Radio frequency welding and ultrasonic welding are also used to produce stitchless seams mainly on polyurethane coated fabrics. All seams produced for outdoor sportswear are tested for hydrostatic head water resistance.

13.3 Water vapour transfer

The transfer of water from one side of a textile to the other is affected by a combination of mechanisms. The surface of a textile may have been wetted by wicking, the wicked moisture then may have been absorbed into the textile structure. The absorbed water may have been transferred by diffusion within the textile structure which may have been followed by desorption of the transferred water to the other side of a textile. These mechanisms are generally determined by the type of fibres used in the construction of the textiles (Adler and Walsh, 1984). For textiles made from absorbent fibres, such as natural fibres and regenerated fibres, water is absorbed by hygroscopic fibres, transported through the swollen fibres, and evaporated from the outer surface of the textile. For textiles made from synthetic fibres water is taken up into the capillary spaces between fibres and yarns.

The mechanisms involved in each stage of the above process are complex and interrelated. In this chapter, only the mechanism of water vapour transfer by diffusion will be discussed as it is regarded as the most important mechanism to consider when assessing the benefits of the outer layer of outdoor sportswear.

Diffusion is the process by which matter is transported from one part of the system to another as a result of random molecular motions. The mathematical theory of diffusion in isotropic substances is based on the hypothesis that the rate of transfer of a diffusing substance through a unit area of a section is proportional to the concentration gradient measured normal to the section. The rate of transport of the diffusing substance along a plane perpendicular to the concentration gradient is given by Fick's first law (Crank, 1975):

$$F = -D\frac{\partial C}{\partial x} \tag{13.2}$$

where F is the rate of water vapour transfer, C is the concentration of diffusing substance, D is the diffusion coefficient, and x is the space coordinate measured normal to the section.

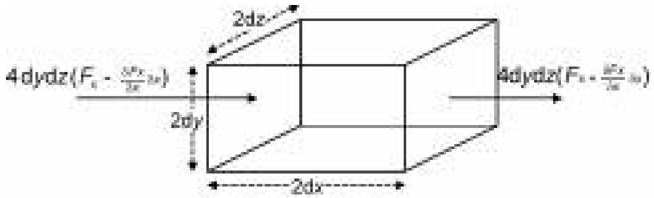
It must be emphasised that the statement expressed mathematically by Equation (13.2) is in general consistent only for an isotropic medium, whose structure and diffusion properties in the neighbourhood of any point are the same relative to all directions. Fick's first law of diffusion can only be directly applied to diffusion in the steady state where concentration is not varying with time. From Equation (13.2), a differential equation giving the relationship between concentration, position and time (t) can be derived if an element of thickness (x) and unit area (y, z) are considered as shown in Fig. 13.3. From Fig. 13.3, if there is a gradient of concentration only along the x-axis, it becomes one-dimensional diffusion, and then Equation (13.3) can be reduced to Equation (13.4). Equations (13.3) and (13.4) are usually referred to as Fick's second law of diffusion by direct analogy with the equation of heat conduction.

$$\frac{\partial C}{\partial t} = D\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2}\right) \tag{13.3}$$

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \tag{13.4}$$

All researchers who have investigated the mechanism of water vapour transfer by diffusion have agreed that the water vapour transfer rate from the internal side of a fabric to the external environment is directly proportional to the vapour pressure difference between the inner surface of the fabric and that of the ambient air as explained by Fick's law (Fourt and Harris, 1947; Whelan *et al.*, 1955; Weiner, 1970; Ruckman, 1997a).

It is also usual for researchers to evaluate the performance and protection characteristics of different types of waterproof breathable fabrics used in the outer layer of outdoor sportswear using various testing methods developed on



13.3 Diffusion element.

the basis of Fick's law. Such evaluation normally takes place in a laboratory under a standard atmosphere of 20 ºC ± 2 ºC and 65% ± 5% r.h. either without a temperature gradient (such as BS 7209 and ASTM E96-80) or with a temperature gradient (such as ISO 11092). However, water vapour transfer in waterproof breathable fabrics is especially difficult to compare principally because there are many testing methods and measurement technologies in existence in addition to the aforementioned standard testing methods, but also because the conditions during the tests do not reflect the real-life conditions for which waterproof breathable fabrics are designed. In addition, different test methods and techniques often produce conflicting results and therefore much controversy exists as to which methods provide accurate and realistic results (Salz, 1988; Qu and Ruckman, 2001). Nevertheless, it is beneficial to be aware of some fundamental findings from previous research, and these will be explained in the following sections.

13.3.1 Performance and protection under steady state conditions

It is believed that, under steady state conditions, diffusion is affected by factors such as thickness of the fabric and that water vapour is diffused through the inter-yarn spaces, through inter-fibre spaces, through the fibre substance itself, and through the free air spaces within textiles (Whelan *et al.*, 1955; Weiner, 1970; Mecheels, 1971). It has been noticed, however, that the water vapour transfer within waterproof breathable fabrics is affected by the type of material used for waterproofing rather than other factors. When the waterproof breathable fabrics used in the outer layer of outdoor sportswear are tested using the test method described in BS 7209, the rates of water vapour transfer are ranked as follows: microfibre fabrics, cotton Ventiles, PTFE laminated fabrics, porous polyurethane laminated fabrics, hydrophilic fabrics and polyurethane coated fabrics (Ruckman, 1997a), indicating that the type of waterproofing material has a significant effect on the water vapour transfer rate. The typical water vapour transfer rates for waterproof breathable fabrics under steady state conditions are between 50 and 1,500 g/m^2/24 hours.

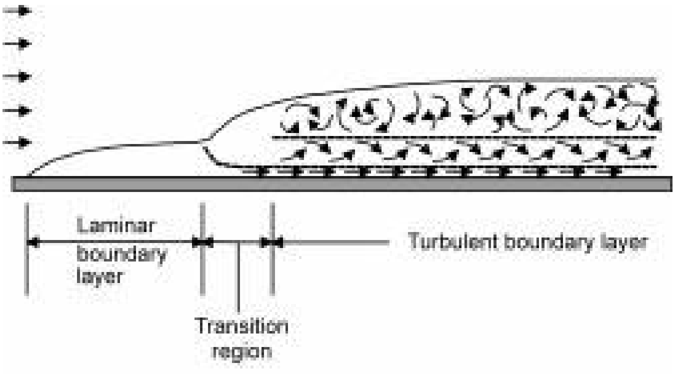
When the water vapour transfer rates at various air temperatures are measured, it is evident that the water vapour transfer rate of various waterproof breathable fabrics at the air temperatures of 10 ºC and 0 ºC show the same sequence as at an air temperature of 20 ºC (Ruckman, 1997a). The difference between the rates for various fabrics becomes closer as the temperature falls, and eventually there is not much difference between water vapour transfer rates. Kim (1999) has also noticed that water vapour transfer through waterproof breathable fabrics is affected not only by the environmental conditions but also by the property of the membrane. This is because waterproof breathable fabrics are laminated or coated with different types of waterproof breathable membrane and this waterproof membrane forms a barrier to water vapour and heat transfer, which results in a rapid build-up of water vapour pressure and a prolonged temperature rise at the inside surface the fabric.

The effect of subzero temperatures on the water vapour transfer of hydrophilic and PTFE laminated fabrics has been studied by Osczevski (1996). It has been found that the water vapour diffusion resistance increases exponentially as temperature decreases because vapour pressure over ice is very low, thus creating a very low vapour pressure difference across the fabric. The effects are greater for fabrics that are hydrophilic membrane laminated or coated than for those that are hydrophobic membrane laminated or coated, because of the vapour concentration dependence of the hydrophilic membrane. However, Bartels and Umbach (2002) have surveyed the water vapour transfer properties of foul weather protective textiles and clothing as a function of temperature (−20 °C, 0 °C and 20 °C) in wearer trials with test subjects in a climatic chamber and found out that there is no indication of temperature dependence of the water vapour resistance of hydrophilic membrane laminates.

Measurement of water vapour transfer rate when there is a temperature gradient revealed that the water vapour transfer rate in the presence of a temperature gradient is widely different from that in the absence of a temperature gradient. The typical water vapour rates for waterproof breathable fabrics under steady state conditions are generally between 2,000 and 8,500 g/m^2/24 hours as opposed to between 50 and 1,500 g/m^2/24 hours. This is because the water vapour pressure at 33 °C is much higher than at the temperatures considered above. The water vapour transfer rates under a temperature gradient are ranked: microfibre fabrics, PTFE laminated fabrics, cotton Ventiles, hydrophilic fabrics, porous polyurethane laminated fabrics and polyurethane coated fabrics (Ruckman, 1997a). This is in agreement with other researchers' findings. Salz (1988) has produced the ranking: microfibre fabrics, PTFE laminated fabrics, porous polyurethane laminated fabrics, hydrophilic fabrics and polyurethane coated fabrics. The results from Holmes (2000) also correspond to the foregoing.

13.3.2 Performance and protection under windy conditions

As explained in the previous section, it is generally believed that water vapour transfer from the outer surface of a fabric to the surrounding atmosphere varies in proportion to the difference between the water vapour pressure at the surface and that of the surrounding air. However, this relationship is not strictly true even in still air because free convection takes place at the outer surface of a fabric. In addition, although the water vapour transfer rate from the internal side of a fabric to the external environment is directly proportional to the vapour pressure difference between the inner surface of the fabric and the ambient air,



13.4 Boundary layers.

this relationship may not be strictly accurate, especially when forced convection takes place at the outer surface of the fabric.

Water vapour transfer from the surface of the human skin to the external environment under windy conditions is governed by three elements in outdoor sportswear. These are the air gap between the surface of the skin and the inner side of the fabric, the structure of the fabric (or fabrics if there is more than one layer in the sportswear assembly), and the existence of a boundary layer caused by forced convection. The water vapour transfer from the outer surface of a fabric to the surrounding atmosphere in forced convection behaves in precisely the same way as the convective heat transfer in these conditions and is proportional to the equivalent resistance to convective heat transfer (Eckert and Drake, 1972; Monteith, 1973; Mitchell, 1974).

There are two main types of air layers in boundary layers: the laminar boundary layer and the turbulent boundary layer, as shown in Fig. 13.4. Starting from the leading edge of the plate, the laminar boundary layer continues to develop until some critical distance. In this layer, fluid elements move in continuous stream lines, without mixing with the fluid in adjacent paths. In the turbulent boundary layer, eddying movements of small fluid elements are superimposed on the main flow resulting in the mixing of the fluid. In real-life conditions, forced convection occurs when air movement develops either laminar or turbulent boundary layers over a surface. Laminar layers cause continuous stream-line wind, and turbulent boundary layers cause a superimposed turbulent wind that tends to break down into a series of eddies (Schlichting, 1968). Under these windy conditions, there is not only diffusion of water vapour through the fabrics, but also mass movement of air through and over them, which evacuates the water vapour. Therefore, it is necessary to observe water vapour transfer under windy conditions, as more often than not the outer layer of outdoor sportswear made of waterproof breathable fabrics will be exposed to wind and various severe environmental conditions.

Convective heat loss, Hc, can be expressed as follows (Monteith, 1973; Mitchell, 1974; Clark *et al.*, 1981):

$$\mathrm{Hc} = \mathrm{Nu}\,k\,(Ts - Ta)/d \tag{13.5}$$

where Nu is the Nusselt number, k is thermal conductivity, Ts is skin temperature, Ta is air temperature, and d is the length of the surface.

The calculation of a rate of heat loss by convection requires the estimation of the Nusselt number, Nu, which expresses the ratio of the actual heat transfer coefficient for convection. The forced convection Nusselt number is given by Bird (1960) as:

$$\mathrm{Nu} = C\,\mathrm{Re}^m \mathrm{Pr}^n \tag{13.6}$$

where C is a constant which depends on the smoothness of the surface, Re is Reynolds number ($\mathrm{Re} = vd/\mu$, where v is air velocity, d is the length of the surface, μ is dynamic viscosity), Pr is the Prandtl number ($\mathrm{Pr} = \mu Cp/k$, where Cp is specific heat, k is thermal conductivity), and m and n are constants which depend on the degree of turbulence.

According to Monteith (1973) and Clark *et al.* (1981), the Nusselt number is defined as follows in the case of real life in which the boundary layer is usually turbulent:

$$\mathrm{Nu} = 0.026\,Re^{0.81}\,\mathrm{Pr}^{0.33} \tag{13.7}$$

It is apparent from the convection heat loss equation that the convective heat loss is proportional to the Nusselt number when the given environmental conditions are the same. Therefore, assuming water vapour transfer by forced convection behaves in precisely the same way as convective heat transfer, it can be said that water vapour transfer and $\mathrm{Re}^{0.81}$ have a linear relationship, and hence water vapour transfer is proportional to $\mathrm{V}^{0.81}$, since this is the form in which wind speed is expressed in the Reynolds number for forced convection. However, this was found not to be the case for waterproof breathable fabrics used in the outer layer of outdoor sportswear. By inserting a layer of waterproof breathable fabric between the surface of the water (the water simulating vapour producing human skin) and the external windy environment, the rate of water vapour transfer decreases such that it is proportional to $\mathrm{V}^{0.5}$ and not $\mathrm{V}^{0.81}$. This suggests that as wind velocity increases, the effect of a layer of fabric on water vapour transfer increases in significance.

When waterproof breathable fabrics are tested using the hot plate method with a temperature gradient, the rates of water vapour transfer are shown to be ranked: microfibre fabrics, cotton Ventiles, PTFE laminated fabrics, hydrophilic fabrics, porous polyurethane laminated fabrics from highest to lowest values at over 2.5 m/s of wind speed (Ruckman, 1997b). It is also the case that the greater the wind speed, and hence the greater the difference in vapour pressure across the fabric, the greater the water vapour transfer.

13.3.3 Performance and protection under rainy conditions

Waterproof breathable fabrics are generally used under severe conditions, and good performance outdoors for a considerable time is regarded as being of primary importance for outdoor sportswear. Effort has therefore been made by some researchers to assess performance under rainy conditions, primarily to determine the fabric's breathability effectiveness when subjected to 100% relative humidity, but also to assess performance under prolonged severe rainy conditions. The results from previous research indicate that waterproof breathable fabrics breathe even in rainy conditions (Keighley, 1985). It was also evident from previous research that water vapour transfer in waterproof breathable fabrics decreases as rain temperature increases. In terms of performance of various types of waterproof breathable fabrics, the rates of water vapour transfer are ranked: PTFE laminated fabrics, cotton Ventiles, porous polyurethane laminated fabrics, hydrophilic fabrics and polyurethane coated fabrics from highest to lowest when the waterproof breathable fabrics were tested with a temperature gradient (Salz, 1988; Ruckman, 1997c).

The breathability of the fabrics under rainy conditions may be explained by reference to the concept of the absolute moisture content of air. The direction of water vapour transfer by diffusion depends on the absolute difference in water vapour concentration. The relation of temperature and relative humidity to the absolute moisture content (Tanner, 1979; Kenneth, 1989) suggests that it is possible for diffusion to occur from an area with less than 100% relative humidity to an area with 100% relative humidity if the concentration gradient is favourable. For example, when the water temperature inside a dish is 33 ºC, and the relative humidity of the air between water level and the inner surface of the fabric is 90%, the absolute moisture content is 4.2%. However, at any given air temperature for rainy conditions, the absolute moisture content does not exceed that of 33 ºC, 90% relative humidity. Consequently, water vapour will diffuse from the air that has a high temperature and low relative humidity to the air that has a lower temperature and higher relative humidity.

For outdoor sportswear, the temperature of the air between the human body and the outer layer of a clothing system is usually higher than that of the outside air and, because of the insensible perspiration emitted by the body, the air inside has a higher moisture content than the air outside, although it has a lower relative humidity than the latter. Therefore, under conditions of steady water vapour transfer in waterproof breathable fabrics, these fabrics worn over a warm and moist human body breathe in rainy conditions.

It has been observed, however, that some waterproof breathable fabrics stop breathing after a certain period (Ruckman, 1997c). There are also differences in the behaviour and the time required to stop breathability for polyurethane coated fabrics, PTFE laminated fabrics and hydrophilic fabrics during prolonged rainy conditions. These are regarded respectively as being the original waterproof breathable fabric, the most common waterproof breathable fabric, and the latest waterproof breathable fabric. The Fibre Research Institute in the Netherlands has evaluated different breathable fabrics using the method developed by The Netherlands Organisation for Applied Scientific Research (TNO) and found that rain not only has a major influence on water vapour transfer but can cause some fabrics to become virtually impermeable in rain owing to blocking of the micropores. They have found out, however, that other fabrics show an increase in water vapour transfer due to the higher vapour gradient when the outer side of a fabric is cooled by rain. This is particularly the case for highly hydrophobic laminates (Bajaj and Sengupta, 1992).

All investigations made on the properties of waterproof breathable fabrics used in outdoor sportswear were based upon the theory that water vapour transfer is governed by Fick's law (Ruckman, 1997a,b,c; Gretton *et al.*, 1997, 1998). Recent developments in waterproof breathable fabrics such as hydrophilic laminated fabrics have, however, demonstrated a different method of transmission of water vapour. Several researchers concentrating on the mechanism of water vapour transfer in such fabrics have reported that water vapour transfer in hydrophilic fabrics does not obey Fick's law but is governed by non-Fickian, anomalous diffusion (Osczevski and Dolhan, 1989; Gibson, 1993; Gretton *et al.*, 1996; Osczevski, 1996). Some researchers have previously noted the humidity-dependence of hydrophilic membranes. Osczevski and Dolhan (1989) used a plexiglass ring device to sandwich four Gore-Tex fabrics, which have hydrophilic coating, and found that the resistance to water vapour diffusion decreased markedly when the relative humidity at the inner surface of the fabrics increased. Keighley (1985) noticed that the breathability of certain rainwear fabrics appeared to increase in rainy conditions. Farnworth *et al.* (1990) employed a sandwich device and obtained the same result: the fabrics with hydrophilic coatings showed a significant decrease in resistance to water vapour diffusion when the relative humidity was high.

13.3.4 Performance and protection under wind-driven rainy conditions

Owing to the technical difficulties of conducting controlled experiments that prevent repeatable results being obtained, few references on the performance of waterproof breathable fabrics under wind-driven rainy conditions exist. However, when experiments under wind-driven rainy conditions with a wind of velocity 2.5 m/s passing across the surface of a waterproof breathable fabric are conducted, it is found that water vapour transfer under wind-driven rainy conditions decreases as rain temperature increases (Ruckman, 1997c). Experiments have shown that the water vapour transfer rate decreases under wind-driven rainy conditions compared with that under rainy conditions for a given temperature. Empirical studies have therefore shown that, assuming constant temperature, wind increases and rain decreases the water vapour transfer rate of a waterproof breathable fabric, giving a ranking in descending order of water vapour transfer performance: windy, dry, wind-driven rainy, rainy.

13.4 The condensation problem in waterproof breathable fabrics for sportswear

Waterproof breathable fabrics for outdoor sportswear are used not only in outdoor conditions but also by individuals engaged in arduous sports activities. If waterproof fabrics are manufactured to be used only to prevent water penetrating the fabrics, these fabrics cannot prevent the formation of condensation from the excessive amount of perspiration produced by the human body. This is particularly serious in some sportswear manufactured from continuously coated fabrics because all the standard polymers which are used for protective clothing have low water vapour permeability. Condensation is, therefore, of particular interest in a discussion of the protective properties of waterproof breathable fabrics when they are used as the outer layer of outdoor sportswear. Condensation occurring in outdoor sportswear results not only in the accumulation of liquid but also in the release of heat, which subsequently affects the vapour concentration and temperature in the adjacent air and causes both heat stress and an uncomfortable sensation of wetness in addition to affecting the rate of water vapour transfer.

Condensation occurs within the fabric whenever the local vapour pressure rises to the saturation vapour pressure at the local temperature (Collier, 1972, Ruckman, 1997d), and therefore occurs when it is easier for water vapour to diffuse into part of the textiles from the skin than it is for it to diffuse away to the environment. Since diffusion is driven by the vapour pressure gradient, although the water vapour transfer rate is high, more water may diffuse in than out. This situation is almost certain to occur when the ambient air temperature is low. When the warm and moist air from the body meets the waterproof breathable fabric, which acts as a cold wall, condensation occurs. Whether or not condensation will accumulate depends on the breathability of the fabric. The process of condensation causes a temperature rise in the fabric, and thus the vapour gradient over the fabric changes. This situation becomes more complex when rain falls on the outside of the fabric. The rain constantly cools the fabric, whilst the condensation of water on the inside constantly heats it.

Keighley (1985) noted that the breathability of certain rainwear fabrics appears to increase in wet conditions. According to Barns and Holcombe (1996), it is also generally believed that the greater the quantity of water present in a fabric, the greater the water vapour transfer demonstrated by the fabric. The increase in water vapour transfer rate with increasing amount of condensation has been reported (Ren and Ruckman, 1999), together with observation that the higher the amount of condensation, the higher the water vapour transfer through waterproof breathable fabrics (Ren and Ruckman, 2001). The effect of other garment layers and condensation in clothing systems incorporating waterproof breathable fabrics has also been studied by Gretton *et al.* (1998). The results obtained from laboratory testing and field trials confirmed that condensation occurred at ambient temperatures below 10 °C.

The water vapour transfer mechanism when condensation is present can be further explained using the formula shown below. According to this formula the water vapour transfer rate depends on water vapour transferred through both the area of no condensation and the condensation bearing area as below:

$$\frac{\partial Q}{\partial t} = D_1 \frac{\partial C'}{\partial L} + D_2 \frac{\partial C''}{\partial L} \tag{13.8}$$

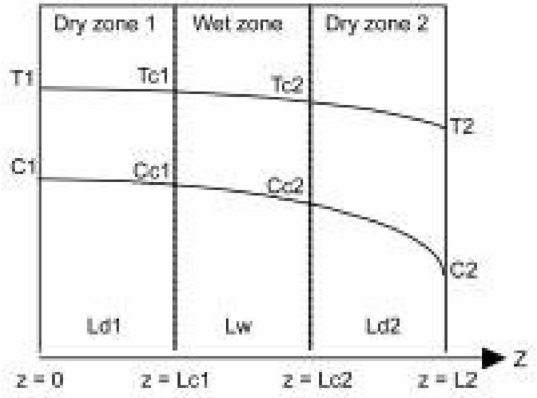
where Q is water vapour transfer through fabric, t is time, C' is vapour concentration on the condensed area between both sides of the fabric, C'' is vapour concentration on the non-condensed area between both sides of the fabric, L is the thickness of the fabric, D_1 is the diffusion coefficient of the vapour molecules through the fabric in the condensed area, and D_2 is the diffusion coefficient of the vapour molecules through the fabric in the non-condensed area.

The vapour concentration difference, ∂C, can be expressed by the relation (Fourt and Harris, 1947):

$$\partial C = \partial p M_w / RT \tag{13.9}$$

where ∂p is vapour pressure difference, M_w is molecular weight of water, R is the gas constant, and T is absolute temperature.

It can then be clearly seen from Equations (13.8) and (13.9) that the water vapour transfer for a given temperature depends on the vapour concentration difference and diffusion coefficient. The vapour concentration difference relies on the vapour pressure difference. When the vapour concentrations at the two faces of the fabric are at saturation level, condensation occurs throughout the entire thickness of the fabric. When the vapour concentration at the boundaries is less than the saturation level for the local temperature, condensation can occur over some region within the fabric. Thus condensation occurring in the fabric forms a wet zone separated by two dry zones, or dry–wet–dry. It has been observed that, in contrast to a normal fabric (for which the temperature and vapour concentration profiles are shown in Fig. 13.5), in a three-layer waterproof breathable fabric, one boundary of the dry–wet zone is located within the lining layer and the other boundary of the wet–dry zone is located at the interface between the lining layer and the waterproof layer, as shown in Fig. 13.6 (Ren and Ruckman, 2004). The extent of the wet region in the three-layer waterproof fabrics increases with condensation, whilst the extent of the dry region decreases. However, the changes in the extent of dry region near the external air is constant, implying that the extension of the condensation mainly

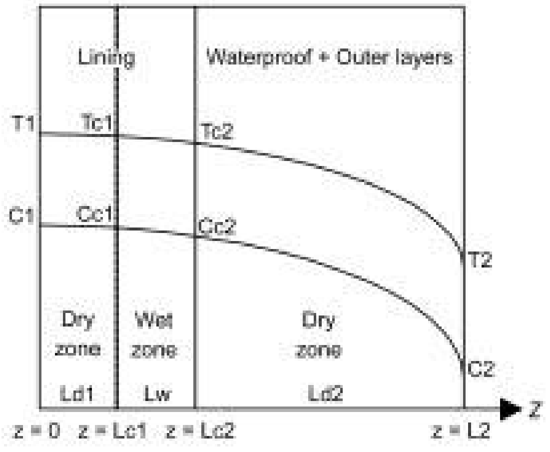


13.5 Temperature and vapour concentration in normal fabrics.

develops towards the direction of the hot side rather than the cold side. It has been suggested that the condensation problem may be solved by changing some physical properties of a three-layer waterproof breathable fabric. The water vapour transfer out of the fabric can be improved, and consequently the formation of condensation reduced, by decreasing the thickness of the waterproof membrane and outer fabric or by decreasing the average diffusion coefficient of the outer layer and membrane.

13.5 Conclusions

In this chapter, the water resistance and water vapour transfer properties of waterproof breathable fabrics used for the outer layer of outdoor sportswear



13.6 Temperature and vapour concentration in three-layer waterproof breathable fabrics.

have been discussed. Since outdoor sportswear is, in general, exposed to low temperatures, to wind, to rain, and to occasional severe conditions of wind-driven rain, the properties of the most frequently used waterproof breathable fabrics such as cotton Ventile fabrics, microfibre fabrics, PTFE laminated fabrics, polyurethane laminated fabrics and hydrophilic fabrics when they are exposed to such environmental conditions, have been the focus of this discussion.

It is evident that the various waterproof breathable fabrics currently used for outdoor sportswear tend to perform exceedingly well with respect to resistance to both penetration into the fabric and through the fabric. However, in terms of water vapour transfer, i.e. breathability of fabric which contributes to wearer comfort, there still is not a single waterproof breathable membrane and fabric that could claim to be truly breathable under severe environmental conditions. All waterproof breathable fabrics developed using various principles behave differently under different conditions in terms of water vapour transfer and the formation of condensation. Wind increases and rain decreases the water vapour transfer rate of a fabric, giving in descending order of water vapour transfer performance: windy, dry, wind-driven rainy, rainy. There is therefore still a need for future generations of waterproof breathable fabrics to be developed that can provide more effective breathability whilst retaining waterproofness under the difficult environmental conditions under which sportswear made from these fabrics is used.

13.6 References

Adler, M.M. and Walsh, W.K. (1984), ‘Mechanisms of transient moisture transport between fabrics’, *Textile Research Journal*, 54(5), 334–343.

Bajaj, P. and Sengupta, A.K. (1992), *Protective Clothing*, The Textile Institute, Manchester.

Barns, J.C. and Holcombe, B.V. (1996), ‘Moisture sorption and transport in clothing during wear’, *Textile Research Journal*, 66(12), 777–786.

Bartels, V.T. and Umbach, K.H. (2002), ‘Water vapour transport through protective textiles at low temperatures’, *Textile Research Journal*, 72(10), 899–905.

Bird, R.B. (1960), *Transport Phenomena*, Wiley, New York.

Clark, J.A., Owen, J.M. and Turner, A.B. (1981), ‘The physics of the microclimate’, in Cena, K. and Clark, J.A. (eds), *Bioengineering Thermal Physiology and Comfort*, Elsevier Scientific, Oxford.

Collier, J.G. (1972), *Boiling and Convection*, McGraw-Hill, New York.

Crank, J. (1975), *The Mathematics of Diffusion*, Clarendon Press, Oxford.

Eckert, E.R.G. and Drake, R.M. Jr (1972), *Analysis of Heat and Mass Transfer*, McGraw-Hill, New York.

Farnworth, B., Lotens, W.A. and Wittgen, P. (1990), ‘Variation of water vapour resistence of microporous and hydrophilic films with relative humidity’, *Textiles Research Journal*, 60(1), 50–53.

Fourt, L. and Harris, M. (1947), ‘Diffusion of water vapour through textiles’, *Textile*

Research Journal, 17(5), 256–263.

Gibson, P.W. (1993), ‘Factors influencing steady state heat transfer and water vapour transfer measurements for clothing materials’, *Textile Research Journal*, 63(12), 749–764.

Gretton, J.C., Brook, D.B., Dyson, H.M. and Harlock, S.C. (1996), ‘A correlation between test methods used to measure moisture vapour transmission through fabrics’, *Journal of Coated Fabrics*, 25, April, 301–310.

Gretton, J.C., Brook, D.B., Dyson, H.M. and Harlock, S.C. (1997), ‘The measurement of moisture vapour transmission through simulated clothing systems’, *Journal of Coated Fabrics*, 26, January, 212–220.

Gretton, J.C., Brook, D.B., Dyson, H.M. and Harlock, S.C. (1998), ‘Moisture vapour transport through waterproof breathable fabrics and clothing systems under a temperature gradient’, *Textile Research Journal*, 68, 936–941.

Holmes, D. (2000), ‘Waterproof breathable fabrics’, in Horrocks, A.R. and Anand, S.C. (eds), *Handbook of Technical Textiles*, Woodhead Publishing Limited, Cambridge.

Keighley, J.H. (1982), ‘Advances in clothing performance and design for protection from the cold’, *Edith Clarke Lecture 1982*, University of Surrey.

Keighley, J.H. (1985), ‘Breathable fabrics and comfort in clothing’, *Journal of Coated Fabrics*, 15, October, 89–105.

Kenneth, W. Jr (1989), *Thermodynamics*, 5th edition, McGraw-Hill, New York.

Kim, J.O. (1999), ‘Dynamic moisture vapour transfer through textiles, part III: effect of film characteristics on microclimate moisture and temperature changes’, *Textile Research Journal*, 69(3), 193–202.

Kissa, E. (1984), ‘Repellent finishes’, in Lewin, M. and Sello, S.B. (eds), *Handbook of Fibre Science and Technology Vol. 1: Chemical Processing of Fibres and Fabrics: Part B*, Marcel Dekker Inc., New York.

Lomax, G.R. (1991), ‘Breathable, waterproof fabrics explained’, *Textiles*, no. 4, 12–16.

Mecheels, J. (1971), ‘Concomitant heat and moisture transmission properties of clothing’, in *Shirley Institute 3rd Seminar: Textiles in Comfort*, Manchester.

Mitchell, D. (1974), ‘Convective heat transfer from man and other animals’, in Monteith, J.L. and Mount, L.E (eds), *Heat Loss from Animals and Man*, Butterworth, London.

Moilliet, J.L. (1963), *Waterproofing and Water-repellency*, Elsevier, London.

Monteith, J.L. (1973), *Principles of Environmental Physics*, Edward Arnold, London.

Osczevski, R.J. (1996), ‘Water vapour transfer through a hydrophilic film at subzero temperature’, *Textile Research Journal*, 66(1), 24–29.

Osczevski, R.J. and Dolhan, P.A. (1989), ‘Anomalous diffusion in a water vapour permeable, waterproof coating’, *Journal of Coated Fabrics*, 18, April, 255–258.

Parys, M. (1994), *Coating*, Eurotex, Guimarães, Portugal.

Qu, J. and Ruckman, J.E. (2001), ‘A new mechanism for the measurement of water vapour transfer in high performance fabrics’, in *World Congress 2001: High Performance Textiles*, Bolton.

Ren, Y.J. and Ruckman, J.E. (1999), ‘Effect of condensation on water vapour transfer through waterproof breathable fabrics’, *Journal of Coated Fabrics*, 29(1), 20–36.

Ren, Y.J. and Ruckman, J.E. (2001), ‘Water vapour transfer in wet waterproof breathable fabrics’, *Journal of Coated Fabrics*, 32(3), 165–175.

Ren, Y.J. and Ruckman, J.E. (2004), ‘Condensation in three-layer waterproof breathable fabrics for clothing’, *International Journal of Clothing Science and Technology*, 16(3), 335–347.

Ruckman, J.E. (1997a), 'Water vapour transfer in waterproof breathable fabrics, part 1: under steady state conditions', *International Journal of Clothing Science and Technology*, 9(1), 10–22.

Ruckman, J.E. (1997b), 'Water vapour transfer in waterproof breathable fabrics, part 2: under windy conditions', *International Journal of Clothing Science and Technology*, 9(1), 23–33.

Ruckman, J.E. (1997c), 'Water vapour transfer in waterproof breathable fabrics, part 3: under rainy and windy conditions', *International Journal of Clothing Science and Technology*, 9(2/3), 141–153.

Ruckman, J.E. (1997d), 'Analysis of simultaneous heat and water vapour transfer through waterproof breathable fabrics', *Journal of Coated Fabrics*, 26, 293–307.

Salz, P. (1988), 'Testing the quality of breathable textiles', in Mansdorf, F.Z. and Nielson, A.P. (eds), *Performance of Protective Clothing: Second Symposium, ASTM Special Technical Publication 989*, American Society of Testing and Materials, Philadelphia.

Schlichting, H. (1968), *Boundary-Layer Theory*, Pergamon Press, London.

Scott, R.A. (2000), 'Textiles in defence', in Horrocks, A.R. and Anand, S.C. (eds), *Handbook of Technical Textiles*, Woodhead Publishing Limited, Cambridge.

Tanner, J.C. (1979), 'Breathability, comfort and Goretex laminates', *Journal of Coated Fabrics*, 8, April, 312–322.

Uedelhoven, W. and Braun, W. (1991), 'Testing the hydrostatic pressure resistance of membrane materials', *Melliand Textilberichte*, 72(3), E71.

Ward, D. (1998), 'Growing global interest in weatherproof membranes', *Textile Month*, March, 14–17.

Weiner, L.I. (1970), 'The relationship of moisture vapour transmission to the structure of textile fabrics', *Textile Chemists and Colourists*, 2(22), 378–385.

Whelan, M.E., MacHattie, L.E., Coodings, A.C. and Turl, L.H. (1955), 'The diffusion of water vapour through laminate with particular reference to textile fabrics', *Textile Research Journal*, 25(3), 197–222.